TONGUE DRIVE: A WIRELESS TONGUE-OPERATED ASSISTIVE TECHNOLOGY FOR PEOPLE WITH SEVERE DISABILITIES

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TONGUE DRIVE: A WIRELESS TONGUE-OPERATED ASSISTIVE TECHNOLOGY FOR PEOPLE WITH SEVERE DISABILITIES

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[To my parents whose love and unconditional support made all this possible.]

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SUMMARY

The main objective of the presented research is to design, fabricate, fully characterize, and assess the usability and functionality of a novel wireless tongue-operated assistive technology, called Tongue Drive System (TDS), that allows individuals with severe physical disabilities (such as quadriplegics) to effectively access computers, drive powered wheelchairs, and control environments using their voluntary tongue motion. The system can wirelessly detect users' tongue movements using an array of magnetic sensors, and a magnetic tracer secured on the tongue, and translate them into a set of user-defined commands in real time, which can then be used to communicate with target devices in users' environment. The principal advantage of the TDS is that a combination of magnetic sensors and a small permanent magnet can capture a large number of tongue movements, each of which can represent one specific command. A set of dedicated tongue movements can be configured as specific commands for each individual user based on his/her preferences, lifestyle, and remaining abilities. As a result, this technology can benefit a wide range of potential users with different types of disabilities.

The work carried out in this dissertation is largely split into three portions: (1) Development, fabrication and characterization of external TDS (eTDS) prototypes to verify the concept of TDS that is detecting and extracting user's intention through their voluntary tongue motion, utilizing a combination of magnetic sensors and a small magnet, as well as the application of this idea in the context of assistive technology. This part of the work is presented in Chapters IV, V and VI. (2) Assessment of the TDS performance in medium term usage for both computer access and wheelchair control. The main

purpose of this work was to gain valuable insight into the TDS learning process and its current limiting factors, which could lead the way in designing new generations of TDS with improved usability. This portion of the work is described in Chapter VII. (3) Development and performance assessment of a multimodal TDS (mTDS), that operates based on the information collected from two independent input channels: the tongue motion and speech. This multimodal system expands the access beyond one input channel and therefore improves the speed of access by increasing the information transfer bandwidth between users and computers. This part of the work is presented in Chapters VIII and IX.

This dissertation has contributed to the innovation and advancement of the start-of-the-art assistive technology research by exploring, realizing and validating the use of tongue motion as a voluntary motor output to substitute some of the lost arm and hand functions in people with severe disabilities for computer access, wheelchair navigation, and environmental control.

CHAPTER I

INTRODUCTION

"*While working towards a cure, there are millions of people with disabilities who deserve an improved quality of life. It is my passion to help disabled individuals, their families and caregivers in ways that will more immediately give them increased independence, day-to-day happiness, and improved access*." -- Dana Reeve

A recent study initiated by the Christopher and Dana Reeve Foundation found that more than 5.4 million people in the U.S., almost one in 50, are living with paralysis. Figure 1.1 shows the major causes of paralysis from spinal cord injuries (SCI) to neuromuscular disorders. 16% of the paralyzed populations (about one million) are complaining that they are completely unable to move and cannot live without continuous help [1]. Each year, more than 50 million people provide care for those who are living with paralysis, which is valued at an annual cost of $306 billion. Moreover, the National Institutes of Health (NIH) reports that 11,000 cases of severe SCI from automotive accidents, acts of violence, and falls add to this population every year. Sadly, 55% of these SCI victims are between 16 and 30 years old, who will need lifelong special care services for the rest of their lives [2]. Considering these important factors, research towards improving the quality of life for this underserved population can potentially have a large societal impact.

Assistive technologies (ATs) can enable individuals with severe disabilities to communicate their intentions to other devices, particularly computers, as a mean to control their environments. This will ease the individuals' need for receiving continuous

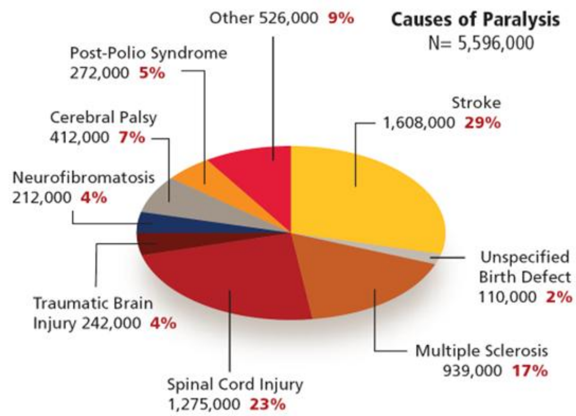


Figure 1.1: Causes of paralysis in the U.S. [1].

help, thus reducing the burden on their family members, releasing their dedicated caregivers, and reducing their healthcare and assisted-living costs. It may also help them to be employed and experience active, independent, and productive lives.

It is generally accepted that an individual with disability plus the appropriate assistive technology can function as a person without limitation [3]. In addition, computing and internet technologies are great equalizers enabling all individuals to have similar vocational and recreational opportunities. Once an individual with disability is “enabled” to access a computer, he/she can potentially do everything that an able-bodied individual can do with that computer. This includes controlling other devices such as powered wheelchairs (PWC), assistive robotic manipulators, and other home/office appliances that are connected to a local area network (LAN) [4]. Even the individual’s own natural or prosthetic limbs can be manipulated to make a move by employing functional electrical stimulation (FES) [5].

Despite the fact that a wide variety of assistive devices are available for people with lower levels of disabilities, those with severe disabilities such as high level SCI patients, who need ATs the most, have very limited options. Even the existing ATs have short comings and impose limitations on the user's quality of life. For example, among ATs those providing alternative control for computer access and wheeled mobility are considered the most important for today's lifestyle since they can potentially improve users' quality of life by easing two major limitations: effective communication and independent mobility [2], [6]. Unfortunately, none of the existing ATs can effectively and safely address both applications. Therefore, users are burdened with learning how to use multiple ATs for various tasks, and switching among them often with the help of a caregiver.

The main objective of the presented research is to advance the state of the art in assistive technology by designing, fabricating, characterizing, and exploring the usability of a novel wireless control device, called Tongue Drive System (TDS) that allow individuals with severe paralysis (quadriplegia) to effectively access computers, drive wheelchairs, and control environments using their voluntary tongue motion with minimum physical, emotional, or psychosocial burden. This new technology can wirelessly detect users' volitional tongue movements inside the oral space utilizing an array of magnetic sensors and a permanent magnetic marker, and translate them into a set of user-defined commands in real time without requiring the tongue to touch or press against anything. These commands can then be used to access a computer, operate a PWC, or control other devices in users' environment. The system can offer its end users multiple control functions over a wide variety of devices, thus, releasing them from the burden of learning to use and switching among different ATs.

CHAPTER II

ORIGIN AND HISTORY OF THE PROBLEM

2.1 What is Assistive Technology?

According to the Technology-Related Assistance for Individuals with Disabilities Act of 1988 (Public Law 100-407) [7], assistive technology is “any item, piece of equipment or product system whether acquired commercially off the shelf, modified, or customized that is used to increase, maintain or improve functional capabilities of individuals with disabilities”. The examples of modern assistive technologies (ATs) include but not limited to wheelchair, prosthetic limbs, hearing aid, and Braille alphabets (Figure 2.1).

The growth and development of modern assistive technology is dotted with events beginning in the 19th century. In 1808, Pellegrino Turri of Italy built the first typewriter for his blind friend to help her write legibly. In 1821, Louis Braille developed a 6-dot cell based language for blind people to read and write, which later named as Braille system, revolutionized written communication for the blind. During the Civil War in the United States, great strides were made in the development of prostheses, especially for the lower limb. A socket developed by Dubois L. Parmelee in 1863 featured the first suction attachment of lower limb prosthesis [8]. Hearing aids, that amplify sounds for people with hearing impairments, were first patented in the 1890s. Its major function of amplifying sound has not changed over the years. In 1933, Harry Jennings and his disabled friend Herbert Everest, both mechanical engineers, invented the first lightweight, steel, foldable wheelchair [9], which was the earliest wheelchair similar to what is in modern use today.

(a) (b) (c) (d)

Figure 2.1: Examples of modern assistive technology: (a) Wheelchair, (b) Prosthetic limbs, (c) Hearing aid, and (d) Braille Alphabets.

The modern assistive technology appliances and industries have grown rapidly over the past decades due to the innovations in new materials and technologies. Significant efforts have been made to improve the quality of life (QoL) of the people with severe disabilities, such as individuals completely paralyzed as a result of injury or neurological diseases. Many researchers are working towards helping this population by leveraging the recent advancements in the neurosciences, material sciences, microelectronics, wireless communications, and computing in developing advanced assistive technologies. These technologies will potentially enable individuals with severe disabilities to communicate their intentions to other devices, particularly computers, as a mean to control their environments. ATs will also ease the individuals' needs for receiving continuous help, thus reducing the burden on their family members, releasing their dedicated caregivers, and reducing their healthcare and assisted-living costs. It may also help them to be employed and experience active, independent, and productive lives.

2.2 State-of-the-Art Assistive Technologies

Up until now, very few high-tech ATs have made a successful transition outside of the research laboratories into the consumer market to be widely used by severely disabled individuals. Many factors including financial, technical, psychophysical, and ease of use determine the acceptance rate of an assistive device.

One category of assistive technologies rely on the users' natural pathways to their brains, which are either completely unaffected or only partially impaired by the neurological injuries or diseases, to establish an indirect communication channel between the users' brain and target devices (e.g. computers). For instance, cranial nerves are rarely affected even in the most severe cases of SCI, because of being well protected in the skull [10]. Therefore, the majority of SCI patients have normal vision, speech, and facial muscle control. A key advantage of such technologies is utilizing the reasonable bandwidth that is available through those natural pathways, while remaining noninvasive. As a compromise, they may not cover a small percentage of the target population, who has absolutely no motor abilities, such as those suffering from locked-in syndrome [11]. Sip-and-puff switches, head pointers, eye trackers, electromyography (EMG) switches, and speech recognition software are examples of devices in this category.

2.2.1 Sip-n-puff

Sip-n-puff is a simple, low cost, switch based AT, which allows its user to control a powered wheelchair (PWC) by blowing and sucking through a straw (Figure 2.2). Although sip-n-puff has simple operating principle and easy to use, it is slow, cumbersome for complicated commands, and offers very limited flexibility, degrees of freedom (DoF) and adaptability to user abilities. It only has a limited number of direct choices (4 commands), which should be entered in series [12], [13]. Another major limitation of sip-n-puff is the lack of proportional control, as opposed to a joystick, which can provide a much easier and smoother control over different movements, such as acceleration and deceleration of a PWC. Sip-n-puff also requires diaphragm control and may not benefit

Figure 2.2: Sip-n-puff devices require users to suck and blow through a straw to control powered wheelchairs [12], [13].

those who continuously use ventilators.

2.2.2 Head Controllers

Another group of assistive technologies, known as head controllers, are based on replacing hand or finger movements with head movements. Many of these devices were developed to control the computer mouse cursor by correlating the head movements with the cursor movements on the computer screen [14]-[18]. Figure 2.3 shows a variety of such devices that are based on different tracking mechanisms. The Boost Tracer in Figure 2.3a operates based on sensing acceleration of the head while tilting or turning using miniature gyroscopes and accelerometers [19]. Headmaster, shown in Figure 2.3b, has an ultrasonic transmitter that should be placed in front of the user. The position of the user's head is determined from the intensity of the ultrasonic waves received by three head mounted microphones [20]. HeadMouse and Tracker Pro in Figure 2.3c and Figure 2.3d detect the head position by tracking an infrared (IR) beam reflected from a reflector dot attached on the user's forehead, glasses, or hat [21]-[22]. Track IR in Figure 2.3e has an active IR unit that clips to the side of the headsets and is powered by USB, projecting three IR beams directly at the IR receiver mounted on a monitor [23]. Camera Mouse (Figure 2.3f), QualiEye, HandiEye, EyeTwig, Raton Facial, and Hologram are all similar webcam-based

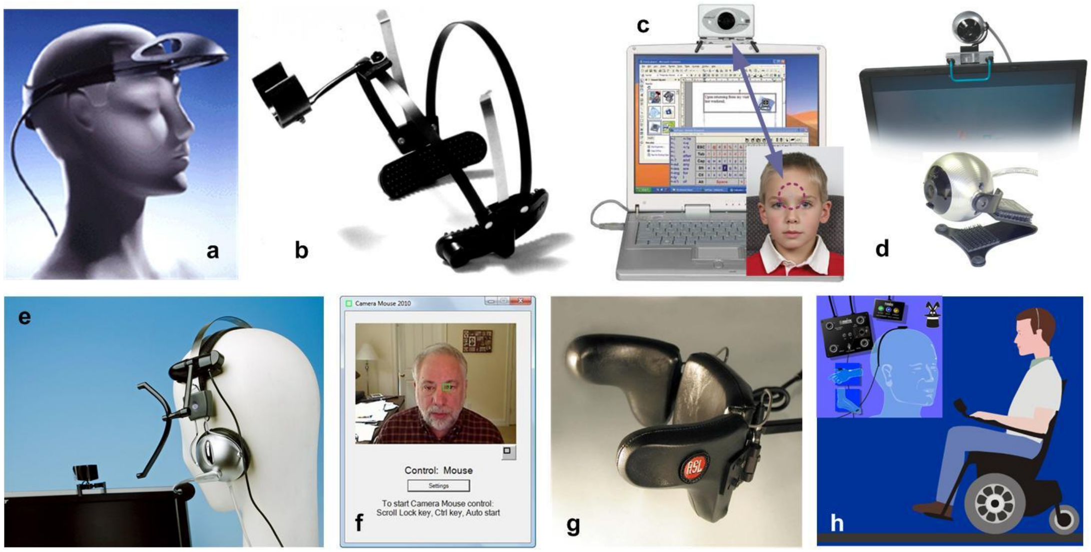


Figure 2.3: Different types of head movement based assistive devices: (a) Boost Tracer based on head acceleration measured by gyroscopes [19], (b) Headmaster based on the intensity of ultrasonic sounds received by three head mounted microphones [20], (c) Headmouse based on infrared reflection received from a head-dot [21], (d) Tracker Pro based on infrared reflection similar to Headmouse [22], (e) TrackIR based on infrared emission received from an active unit mounted on the headset [23], (f) Camera Mouse based on tracking the movements of a user-defined facial feature within a webcam field of view [24], (g) Head array wheelchair controller based on proximity sensors [26], and (h) Magitek wheelchair controller based on head movements measured by accelerometers [27].

software, which operate based on tracking a specific user-defined facial feature or head movements within the webcam field of view [24]-[25].

There are also head controlled devices developed for PWC operation [26]-[28]. For example, a switch-based head array from Adaptive Switch Lab (Figure 2.3g) utilizes three proximity sensors placed inside a headrest for control of a PWC. The sensors mounted inside the right and left wings control movement in those directions while the sensor mounted inside the back pad of the headrest controls movement in the forward or the forward/reverse direction [26]. Magitek (Figure 2.3h) [27] and another similar system developed by Craig et al. [28] use accelerometers to track the head movements and associate them with different wheelchair control commands.

One limitation of head-controlled assistive devices is that only disabled individuals in whom head movement is not inhibited may benefit from them. However, many quadriplegics and locked-in patients do not have good head movements and therefore cannot benefit from any of these devices. Another limitation of these devices is that the user's head should always be in the range within the reach of the assistive device sensors. Otherwise the device cannot be used. Also, the use of head-controlled assistive devices for a long period of time can be quite fatiguing since they exhaust the user's neck muscles, which may already be weak as a result of the disability.

2.2.3 Eye Trackers

Another group of assistive devices operate by tracking eye movements and eye gaze, or more precisely speaking by detecting corneal reflections and tracking pupil position [29]-[36]. In these devices, a computer-mounted camera placed in front of the users, or a miniature optical sensor worn by the users, captures the light, usually, infrared, reflected from the cornea, lens or retinal blood vessel [32]. The information is further analyzed to extract the eye movement from the change of reflection, and is translated to move a cursor on the computer screen. Electrooculograms (EOG) have also been utilized for detecting the eye movements to generate control commands for both computer access and wheelchair control [37]-[42]. The eyes are the origin of a steady electric potential field, which can be modeled by a dipole with its positive pole at the cornea and its negative pole at the retina. Eye movements can cause the change in the orientation of the dipole, which result in a change in the electric potential field around the eye (EOG potential signals). EOG signals can be measured using two pairs of skin electrodes placed at periorbital positions around one eye. By recording and analyzing the changes in EOG signals, eye

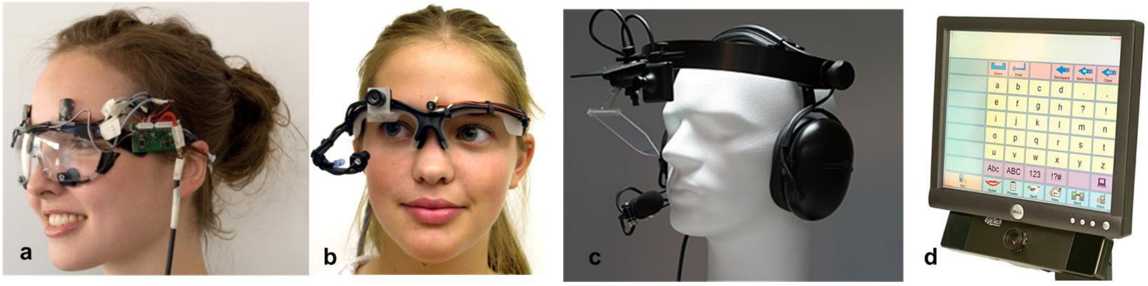


Figure 2.4: Different eye tracking devices: (a) Wearable EOG based eye tracker operates by interpreting bioelectrical signals recorded using surface electrodes attached to the skins around user's eyes [42], (b) Lightweight wearable eyetracking headgear tracks the eye movement using a micro-lens camera [33], (c) iView X HED wearable video-based eye tracker from SensoMotoric Instruments (SMI) works by tracking the pupil position based on corneal reflection [34], and (d) EyeTech TM3 computer-mounted eye tracker based on corneal reflection similar to iView [36].

movements can be tracked and used to move the cursor [42].

Since eyes have evolved as sensory parts of our body, a drawback of the eye-tracking systems is that they affect the users' normal vision by requiring extra eye movements that sometimes interfere with the users' visual tasks. Despite some recent progress, the Midas touch problem, which results in unintended commands being issued when the user just looks at some point and the system considers that as a command, has not yet been entirely resolved for the eye tracking devices [43]. The EOG-based method, shown in Figure 2.4a, requires facial surface EOG electrodes and bulky signal processing unit attached to the goggle that are unsightly and give the user a strange look. This might make the user feel uncomfortable in public places. The wearable video-based eye trackers [33], [34] in Figure 2.4b and Figure 2.4c require bulky headgears, which impose the same appearance issue as EOG-based devices. The computer mounted eye tracking method [36], shown in Figure 2.4d, always requires a camera or display in front of the users for detection or visual feedback, respectively. Therefore, it has the same limitations as the head-controlled devices, requiring the users head to remain within a certain range. In general, camera-based eye trackers are sensitive to the ambient light condition and therefore are not suitable for outdoor wheelchair control. It is worthy to consider that eye trackers are mostly very expensive, usually more than $10,000, which in turn limit their target population.

2.2.4 Electromyography (EMG) Based Controllers

An electromyogram (EMG) signal is the spatio-temporal summation of the electrical signals that are generated from several muscle fibers associated with different motor units during muscle contraction [44]. EMG-based control systems monitor EMG signals from a targeted group of muscles, typically facial [44], [45], neck [46], or shoulder muscles [47], which are associated with the movements that the user is still able to perform. Customized signal processing algorithms can recognize the EMG patterns associated with each movement and produce a set of discrete control commands that can be used to move mouse cursor and perform selection for computer interaction [44]-[46], or replace joystick function to manipulate a PWC [47]-[49].

EMG-based systems are relatively error-prone and need complex muscular interactions [48]. These systems require highly specialized hardware and sophisticated signal process algorithms, therefore resulting in low portability [50]. Additionally, the facial electrode attachment suffers the same cosmetic problem as EOG-based eye tracker.

2.2.5 Voice Controllers

Voice recognition software, such as Dragon Naturally Speaking [51] and Talking Desktop [52], are effective in particular aspects of computer access such as text entry. However, they are not efficient in cursor navigation and sensitive to accents and dialects. There are non-speech sound based voice controllers, i.e. Vocal Joystick [53], developed for cursor control by mapping the different sounds to specific cursor movement directions while associating the energy (loudness) of the voice to the velocity of cursor movement. In these devices, language specificity and accent sensitivity has been removed. However, users might feel uncomfortable and even awkward when using such devices in quiet but public places. There are researchers working on developing voice-based controllers for PWC manipulation [54]-[57]. These devices can provide reasonable bandwidth and have relative short response time. However, they are not safe enough to operate the wheelchair independently, and therefore have to rely on additional autonomous navigation system to avoid collisions. A common problem associated with almost all voice-based controllers is that they can work properly in the indoor and quiet environment, but become inefficient and even completely useless in the outdoor or noisy environment.

2.2.6 Brain-Computer Interfaces

A group of assistive devices, known as brain-computer interfaces (BCIs), directly tap into the source of volitional control, the central nervous system. Such BCIs can potentially provide a broad coverage among users. However, depending on how close the electrodes are placed with respect to the brain, there is always a compromise between invasiveness and bandwidth. Noninvasive BCIs, which utilize either electroencephalographic (EEG) brain activity or near infrared (NIR) signal (Figure 2.5a – 2.5c), have not become popular among users despite being under research and development since early 70's [58]-[68]. Limited bandwidth and susceptibility to noise and interference have prevented these devices from being used for important tasks such as navigating PWCs in outdoor environments, which need short reaction times and high reliability. There are also other issues such as the need for learning and concentration, considerable time for setup and

Figure 2.5: Some of the existing brain computer interfaces (BCIs): (a) Noninvasive surface EEG based BCI, (b) BSI-Toyota EEG based BCI for wheelchair control [66], (c) Honda BCI system combining EEG with NIR [67], (d) Invasive BCIs utilizing electrocorticogram (ECoG) signal [70], and (e) BrainGate invasive BCI based on the neural signals detected by intracranial microelectrodes [73].

removal, and poor aesthetics [69].

Invasive BCIs utilize signals recorded from skull screws, miniature glass cones, subdural electrode arrays (Figure 2.5d), and intracortical microelectrodes [69]-[72]. They have been studied mainly in non-human primates and more recently on limited human subjects (Figure 2.5e) [73]. Invasive BCIs can achieve higher spatial and temporal resolution compared to their EEG-based counterparts. They can also benefit from higher characteristic amplitudes, leading to less vulnerability to artifacts and ambient noise [69]. However, these BCIs are costly and highly invasive. Therefore, they may not be desired by the majority of end users, when less invasive alternatives are available. There are also several technical issues that still need to be resolved such as electrode lifetime, implant size, robust transcutaneous wireless link, efficient neural signal processing, finding

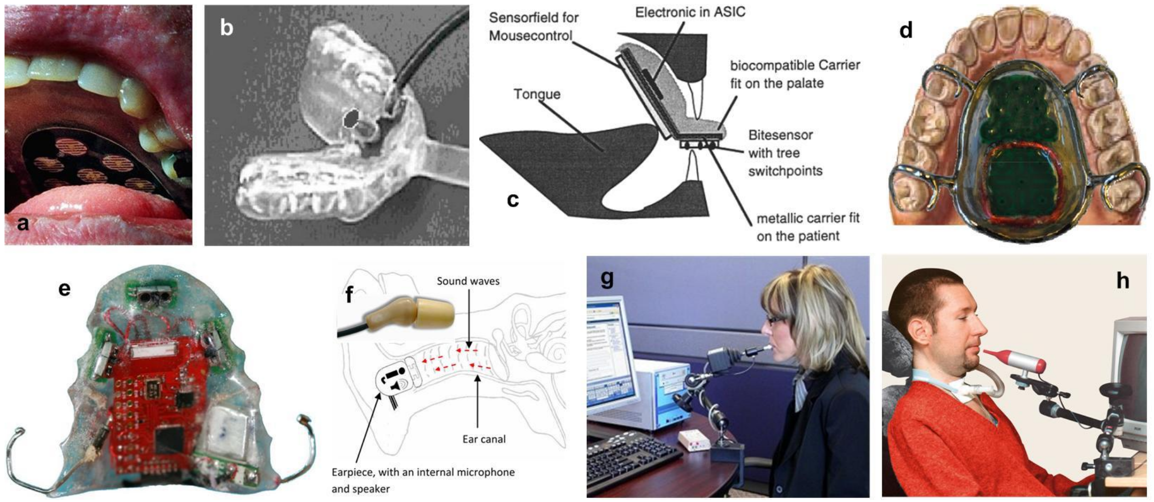


Figure 2.6: Tongue-operated assistive technologies: (a) Tongue Touch Keypad (TTK) [74], (b) Tongue point [75], (c) Tongue mouse [76], (d) Inductive sensor based tongue controller [78], (e) Tongue gesture detector using infrared optical sensors [80], (f) Think-A-Move based on ear canal pressure changes [81], (g) Jouse2, a combination of sip-n-puff and mouth operated joystick [82], and (h) Integra Mouse [83].

optimal target neural populations, and highly portable processing hardware.

2.2.7 Tongue-Operated Devices

There are a group of tongue-operated ATs such as Tongue-Touch-Keypad® (TTK), Tongue Point and Tongue Mouse (Figure 2.6a, 2.6b and 2.6c) [74]-[76]. The TTK consists of 9 switches built onto a mouthpiece that fits in the ceiling of the oral cavity and activates by the touch of the user's tongue [74]. Despite being innovative for the time it was introduced in early 90s, TTK has not been widely adopted because of being bulky and obtrusive [77]. Tongue Point is another AT based on the IBM TrackPoint device used in laptops, which is a small pressure sensitive joystick placed inside the mouth [75]. Even though this device provides proportional control, it is always restricted to a joystick operation and any selection or clicking operation should be performed through additional switches. The tip of the joystick also protrudes about 1 cm into the mouth, which could interfere with speech and ingestion functions. The Tongue-mouse, shown in Figure 2.6c has a sensor module incorporating piezoelectric ceramic sensors and conductive adhesives to connect the sensors to the electronics [76]. The sensors form a matrix, the elements of which can detect strength and position of touch by the tongue. The sensor module is fitted within the oral cavity as a conventional dental plate. However, the sensor module plate is rather large and prevents the user from eating or talking while using this device.

Recently, an inductive sensor based tongue controller (Figure 2.6d) has been developed at the University of Aalborg, Denmark [78], [79]. This device is similar to TTK with 18 inductive switches that are activated with a metallic activation unit in the form of a tongue stud. However, it more or less resembles TTK and Tongue Point in treating tongue as a finger, instead of taking advantage of its ergonomic abilities. Saponas et al. [80] have developed an optical tongue gesture detector, which uses infrared optical sensors embedded within an orthodontic dental retainer to sense tongue gestures (Figure 2.6e). A potential problem with this device is the high probability of unintended commands during speech or ingestion, e.g. “Midas touch” problem. Think-A-Move, shown in Figure 2.6f, measures the pressure changes in the ear canal as a result of tongue movements [81]. It offers only one dimensional control with limited degree of freedom. Most of these devices require bulky objects inside the mouth, which may interfere with speech, ingestion, and sometimes breathing.

There are also a number of tongue- or mouth-operated joysticks such as Jouse2 and Integra Mouse (Figure 2.6g and 2.6h) [82], [83]. These devices can only be used when the user is in the sitting position and require a certain level of head movement to grab the mouth joystick. They also require tongue and lip contact and pressure, which may cause fatigue and irritation over long-term use.

2.3 Summary

A considerable amount of ongoing researches have been dedicated to developing advanced assistive technologies that can potentially improve the quality of life for individuals with severe disabilities. However, the existing ATs either provide their users with very slow and limited control over their environment or they are highly invasive and in early stages of development. Therefore, there is clearly an urgent need to explore alternative means to develop novel ATs that would take advantage of the most recent advancements in sensor technology, computing, and wireless communications, to provide severely disabled individuals with effective access to the computers, and from that channel, access to their PWC, and surrounding environment. In addition to all these technology advancements, the new ATs should also be unobtrusive, low cost, noninvasive, cosmetically inconspicuous, and take patients' needs into consideration so that they can be widely accepted, used and appreciated by their end users.

CHAPTER III

TONGUE DRIVE SYSTEM

3.1 Why Tongue?

The motor homunculus in Figure 3.1 shows that tongue and mouth occupy a significant amount of sensory and motor cortex in the human brain that rivals that of the fingers and the hands. Hence, they are inherently capable of sophisticated motor control and manipulation tasks with many degrees of freedom, which is evident from its role in speech and ingestion [10]. The tongue is connected to the brain via hypoglossal nerve, which generally escapes severe damage in spinal cord injuries (SCIs) and most neuromuscular diseases. As a result, even patients with high level SCIs still maintain intact tongue control capabilities. The tongue can move rapidly and accurately within the oral cavity, which indicate its capacity for wideband indirect communication with the brain. Its motion is intuitive and unlike EEG-based brain computer interfaces (BCIs), does not require thinking or concentration. The tongue muscle has a low rate of perceived exertion and does not fatigue easily [77]. Therefore, a tongue based device can be used continuously for several hours as long as it allows the tongue to freely move within the oral space. The motoneurons controlling tongue muscles receive a wealth of vestibular input and the position of the tongue body is reflexively adjusted with changes in the body position. Therefore, unlike many other devices, which require the user to sit in front of a camera or on a wheelchair to be able to use the device, tongue operated devices can be easily used anywhere, and in any position, such as lying in bed. Another advantage of using tongue is that the tongue location inside the mouth can afford its users considerable

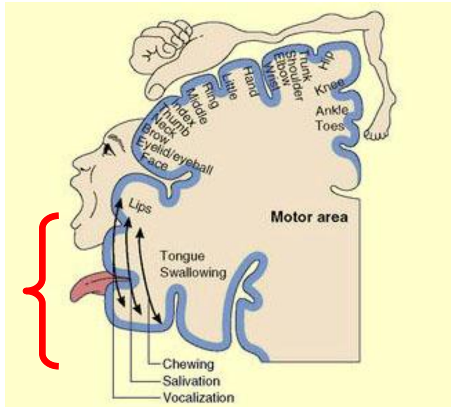


Figure 3.1: Tongue and mouth in the motor homunculus [10].

privacy, which is especially important for people with disabilities, who do not want to be considered different from their able-bodied counterpart. Finally, unlike some BCIs that use neural signals from the motor cortex, which require implanting electrode arrays on the surface of the brain, noninvasive access to the tongue motion is readily available without penetrating the skin.

3.2 Tongue Drive System Overview

Tongue Drive System (TDS) is a minimally invasive, unobtrusive, tongue-operated, wireless, and wearable assistive technology (AT) that can enable people with severe disabilities to control their environment, such as access computers or driving wheelchairs using nothing but only their volitional tongue movements. The system wirelessly detects several specific tongue positions or movements inside the oral space, and translates them into a set of user-defined commands in real time without requiring the tongue to touch or press against anything. These commands can then be used to communicate with a variety of devices in users' environment [84], [85].

Conceptually, TDS consists of an array of magnetic sensors, either mounted on a dental retainer inside the mouth, similar to an orthodontic brace (intraoral TDS,

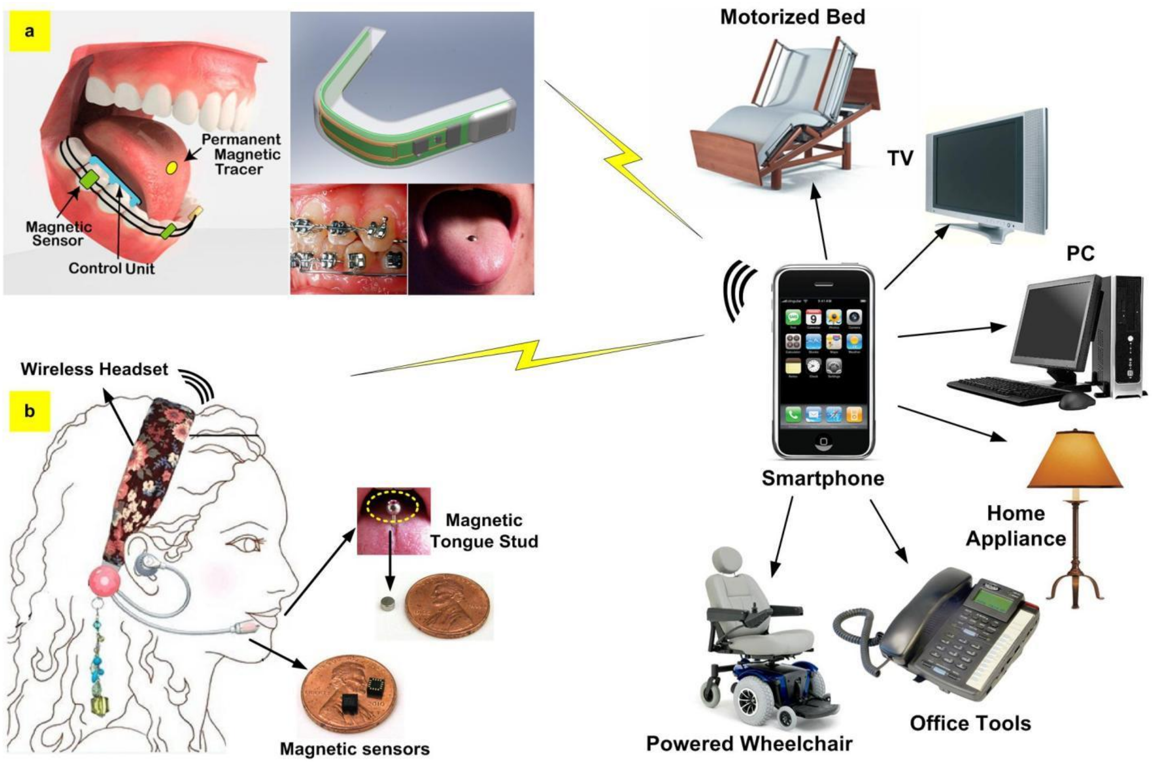


Figure 3.2: Block diagram of Tongue Drive System: (a) intraoral TDS with magnetic sensors and control unit located on a dental retainer, and (b) external TDS with magnetic sensors and control unit mounted on a headset.

Figure 3.2a) or on a headset outside the mouth, similar to a head-worn microphone (external TDS, Figure 3.2b), and a small permanent magnetic tracer, secured on the tongue. The magnet can be temporarily attached to the tongue using tissue adhesives. For long term usage, however, the user should receive a tongue piercing and wear a customized magnetic tongue stud with the magnet embedded. Alternatively, the magnet can be coated with biocompatible materials, such as titanium or gold, and implanted under the tongue mucosa. The magnetic field generated by the tracer varies inside and around the mouth with the tongue movements. Since the human tissue is transparent to DC or low frequency magnetic field, these variations can be detected by the magnetic sensors and wirelessly transmitted to a smart phone, such as an iPhone, or a personal computer (PC), which can be worn by the user or attached to his/her powered wheelchair (PWC). A sensor signal processing (SSP) algorithm running on the PC or smartphone classifies the sensor signals and converts them into user-defined control commands, which are then wirelessly communicated to the target devices in the user's environment [84]-[90].

3.3 Significance of the Presented Technology

The principal advantage of the TDS is that a few magnetic sensors and an inherently wireless small permanent magnet can capture a large number of tongue movements, each of which can represent a specific command. A set of dedicated tongue movements can be tailored for each individual user based on his/her mouth anatomy, preferences, lifestyle, and remaining abilities, and mapped onto a set of customized functions for environmental access. Therefore, TDS can benefit a wide range of potential users with different types of disabilities because of its adaptive operating mechanism. By tracking tongue movements in real time, TDS also has the potential to provide its users with proportional control, which is easier, smoother, and more natural than the switch-based control for complex tasks such driving a PWC in confined spaces [91], [92]. The tongue gestures associated with the TDS commands can be defined in a way that they are sufficiently different from tongue motions originated from involuntary or reflexive tongue movements resulted from speech, swallowing, coughing, or sneezing. In addition, a specific tongue command can be defined to switch the TDS between standby and operational modes when the users intend to eat or engage in a conversation. As a result, the "Midas touch" problem, which is an important reliability issue and has not been completely resolved in some other ATs such as eye trackers, can be avoided in TDS. Using TDS does not require users' tongue to touch or push against anything. This can significantly reduce the tongue fatigue, which is an important factor that affects the acceptability of ATs, and therefore result in greater user satisfaction and technology adoption rate. The TDS headset can be equipped with additional transducers, such as a microphone or motion sensors, and combined with commercial voice recognition software and customized graphical user interface (GUI) to create a "single" integrated, multimodal, multifunctional system, which can be used in a variety of environments for multiple purposes.

3.4 Research Outline

The presented research on the Tongue Drive System has mainly focuses on two areas: (1) Technology development. This part of work was dedicated to developing and refining external TDS (eTDS) prototypes, both hardware and software, including miniature and low power electronics, reliable wireless communication link, customized SSP algorithms, ergonomic headset design as well as user-friendly GUIs [84]-[88]. The goal was to take advantage of the latest technology advancements in sensor, microelectronics, wireless communication, signal processing and mobile computing to develop a new low power wireless wearable assistive device that is smaller, faster, more powerful, more accuracy and more reliable than any of its competitors. (2) Performance evaluation and usability assessment. This is the non-technical aspect of the project, in which the functionality and usability of TDS in both computer access and PWC control was extensively evaluated by able-bodies subjects and the patients with high level SCIs [87]-[90]. This work is as important, if not more important than the technology development part of the research, since the valuable data and users feedback yielded from these human trials are the best guidance to lead the way in developing and improving the next generation of the TDS technology. It is well accepted that it is not only the functionality of the technology itself, but also the usability, the cost, and even the appearance all together that determine the acceptance rate of an assistive device.

CHAPTER IV

DEVELOPMENT OF EXTERNAL TONGUE DRIVE SYSTEM

Over last five years, we have successfully converted the Tongue Drive System (TDS) from a mere concept to a fully functional system and constantly improved its performance through five generations (Figure 4.1), by shrinking the size and power consumption of the hardware, enhancing the sensor signal processing (SSP) algorithm, and improving its ergonomic factors. The external TDS (eTDS) prototypes Gen-1 to Gen-4 (Figure 4.1a – 4.1d) are considered as early generations and designed to verify and validate the idea of TDS, e.g. using a combination of magnetic sensors and a magnet to detect and extract user' intention through their voluntary tongue movements. They were using the same type of digital magneto-inductive sensors and shared similar design in the wireless control units. The latest version of eTDS prototype Gen-5 (Figure 4.1e), is based on analog magneto-resistive sensors and features much higher speed (sensor sampling rate) compared to its predecessors. The design of Gen-5 mainly focused on improving the system's functionality, reliability, mechanical stability, sensor position adjustability, and battery life time. Gen-5 has been used in the TDS medium term performance assessment to study the learn process of using TDS for both computer access and wheelchair control.

Although these prototypes look quite different from each other, their major components have not changed and remain the same over generations. These components include: 1) A small permanent magnetic tracer attached to the tongue using tissue adhesives, clipping, piercing, or implantation, 2) A wireless headset that houses and mechanically supports a group of sensors as well as other electronics, 3) An assortment of

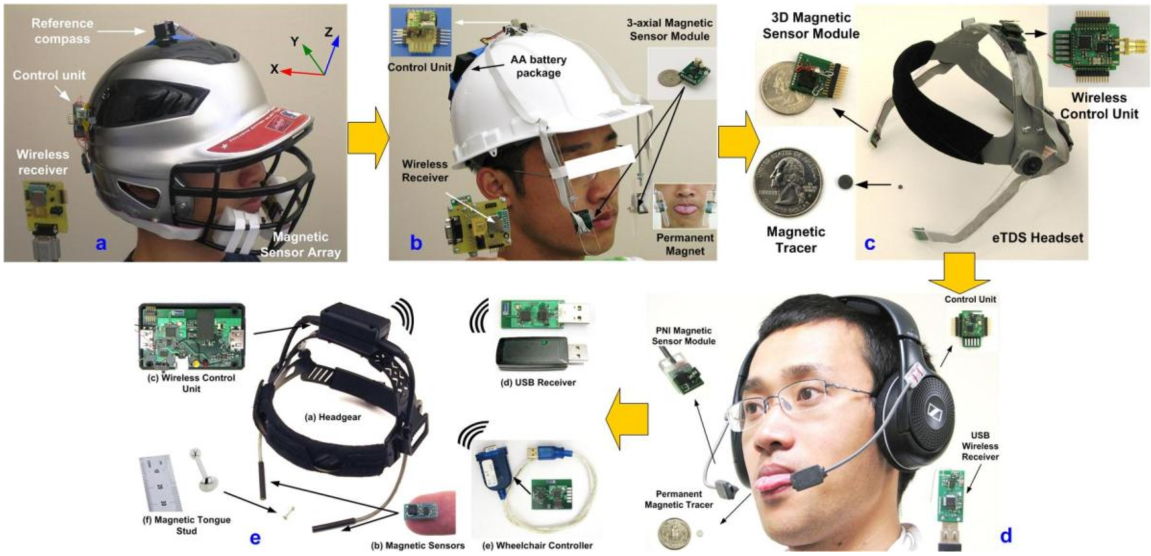
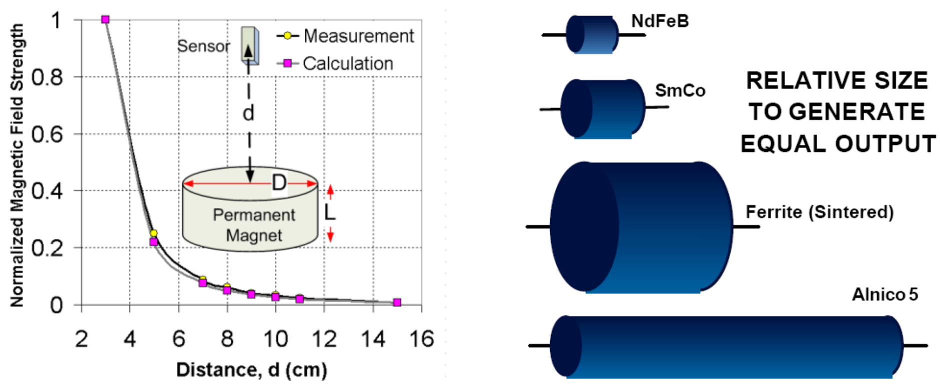


Figure 4.1: Different generations of the TDS prototypes: (a) Gen-1 built on a helmet including a reference compass, (b) Gen-2 built on a hardhat using stereo-differential external magnetic field interference (EMI) cancellation, (c) Gen-3 built on a headgear with smaller PNI sensors, (d) Gen-4 built on a wireless headset and used for clinical evaluation, and (e) Gen-5 built on a headgear with miniature Honeywell AMR sensors to evaluate TDS performance in medium term usage with tongue piercing.

small and low power magnetic sensors to detect the tongue motion plus their interfacing circuitry, 4) A wireless control unit to fuse, packetize, and wirelessly transmit the digitized magnetic sensor samples, 5) A wireless receiver unit that is connected to or included in the PC or smartphone (eventually will include iPhone, Blackberry, Android, and Windows phones) to wirelessly receive the TDS data packets from the headset and deliver them to the PC or smartphone, 6) A driver software running on the PC/smartphone that includes high throughput data communication drivers through I/O ports (such as USB), and 7) SSP algorithm and graphical user interface (GUI), which recognizes the position of the magnetic tracer, hence, the position of the tongue within the oral space.

Each of these components will be described in details in the following sections.



(a) (b)

Figure 4.2: (a) Parameters that affect the magnetic field around a cylindrical magnet. (b) Relative size of different magnetic materials to generate equal output.

4.1 Permanent Magnetic Tracer

The magnetic tracer used in eTDS prototypes is a small permanent magnet, which is an object made of a material that is magnetized and creates its own persistent magnetic field. The main parameters used to describe the characteristics of a permanent magnet are the residual induction (B_r), coercive force (H_c), and peak energy density (BH_{max}). B_r is a measure of the residual magnetic strength of a permanent magnet after the external magnetization field is removed. It is directly related to the field generated by the permanent magnet. For a cylindrical magnet, shown in Figure 4.2a, the on-axis magnetic field strength at distance *d* from a pole of the magnet can be calculated from:

$$B(d) = B_r \times \left(\frac{(d+L)}{\sqrt{4\times(d+L)^2 + D^2}} - \frac{d}{\sqrt{4\times Z^2 + D^2}} \right) \tag{4.1}$$

where *B(d)*, in Gauss, is the magnetic field at distance *d*, *L* and *D* are the length and diameter of the magnet respectively, all in cm. Figure 4.2a also shows that the calculated *B(d)-d* curve closely agrees with the measurement results obtained in the lab environment, therefore validates the equation 4.1. In order to minimize the size of the magnetic tracer, B_r

Table 4.1: Magnetic Tracer Specifications

Specification	Value
Source and type	K&J Magnetics rare-earth super magnet
Magnetic material	Neodymium-Iron-Boron (NdFeB)
Size (diameter/length)	∅ 5.0 mm × 1.6 mm
Residual magnetic strength	B_r = 14,800 Gauss
Peak energy density	BH_{max} = 52 MGOe
Coercive force	H_c > 11,200 Oersted
Surface Field:	B_s = 4,022 Gauss
Weight	0.2 g
Operation temperature	Up to 176 ℉ (80 ℃)

should be maximized. B_r is mainly dominated by the materials of the magnet. Figure 4.2b, which shows the relative size of the most common permanent magnets to generate the same output, indicates that NdFeB, known as rare earth magnet, is the material of choice. Table 4.1 summarizes the specifications of the permanent magnet (K&J Magnetics, Jamison, PA) that was used in the eTDS prototypes.

The magnetic tracer can be temporarily attached to users' tongue with tissue adhesive. To eliminate the risk of the magnetic tracer being detached and inadvertently chewed, swallowed, or aspirated, a thin but strong string, such as dental floss, is attached to the magnet using super glue before coating the magnet with medical grade epoxy and silicone (see Figure 4.3a). The other end of the string is knotted to the eTDS headset. With the string in place, even if the user swallows or aspirates the magnet, it can be easily extracted.

Another way to attach the magnetic tracer to the users' tongue is through tongue piercing (Figure 4.3b). In this case, small magnetic tracers are completely encased in a laser welded titanium bead or vacuum set dental acrylic in an otherwise standard straight tongue stud (also known as tongue ring or tongue jewelry). The magnetic bead has been

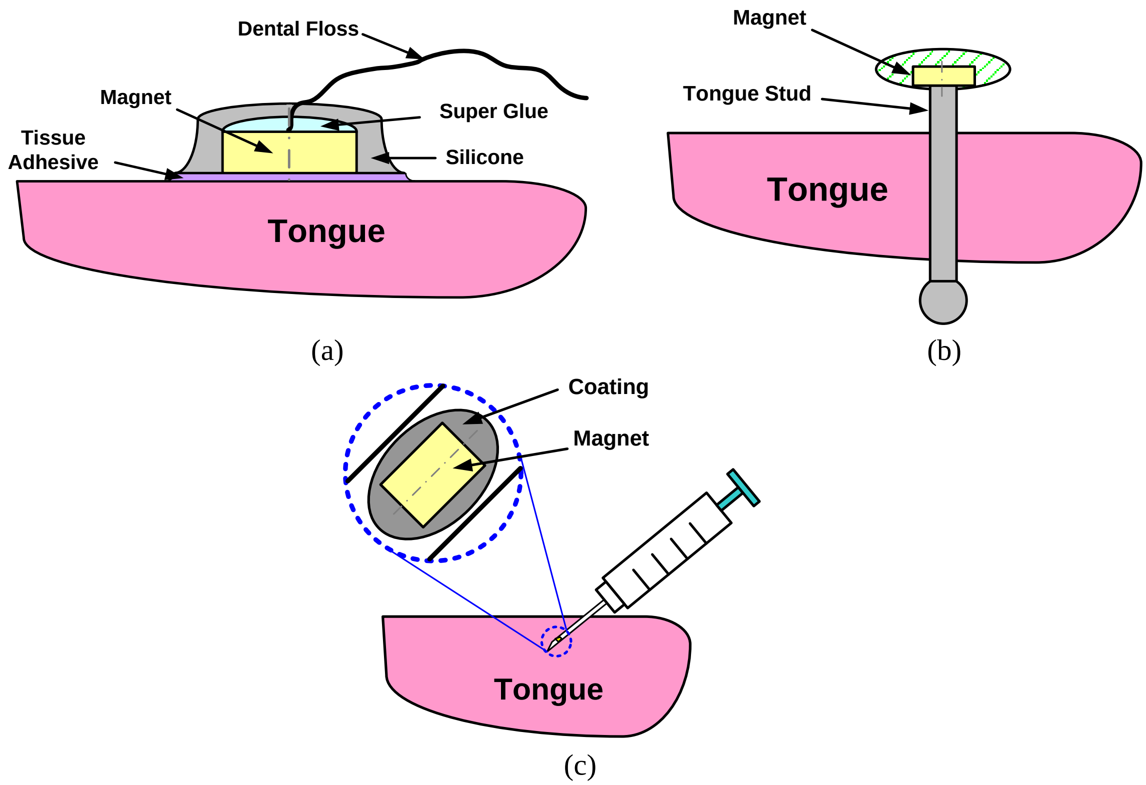


Figure 4.3: Three different ways for attaching the magnetic tracer to the tongue: (a) adhesives, (b) tongue piercing, and (c) tongue implantation.

welded to the post. The lower bead is screwed on with a large number of fine threads.

There are also smaller magnets (Ø1.6 mm $\times$ 0.8 mm) commercially available with the same residual magnetic strength. These smaller magnets can be directly injected under the tongue mucosa using a medical syringe and a hypodermic needle after they are coated with inert biocompatible materials, such as Parylene, polyimide, silicone, gold, titanium, platinum, or ceramics, as shown in Figure 4.3c.

4.2 Wireless Headset

Wireless headset is a key component of the TDS. It contains a group of magnetic sensors to detect the tongue motion, plus a wireless control unit to packetize and wirelessly transmit the magnetic data samples. We have used commercially available equipment, such as

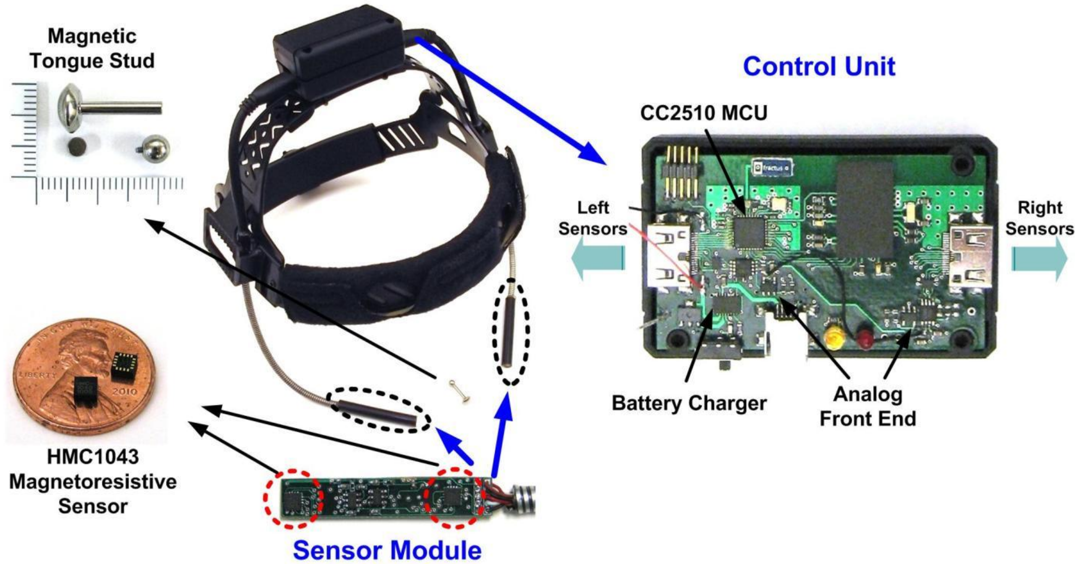


Figure 4.4: The major components of the eTDS prototype Gen-5 wireless headset, built using only commercial off-the-shelf components, including a headgear.

baseball helmet (Gen-1), hard hat (Gen-2), headgear (Gen-3 and Gen-5), and a commercial wireless headset (Gen-4) as the main structure of the headset to mechanically house and support the electronics. Figure 4.4 shows the latest version of eTDS prototype (Gen-5) as an example. In this prototype, the wireless headset is equipped with a pair of goosenecks, each of which bilaterally holds two magneto-resistive sensors near the subjects' cheeks, symmetrical to the sagittal plane. A miniaturized control unit is located on top of the headset and receives its power from a pair of AAA batteries enclosed in the same box.

4.2.1 Magnetic Sensors

Small magnetic sensors have been widely integrated in vehicles, mobile phones, medical devices, and etc. for navigation, speed, position and angular sensing. The other applications of magnetic sensors include measuring currents, correcting the drifts of gyroscopes, detecting unexploded ordnance, space exploration, and measuring the magnetic fields generated by the brain [93]-[95]. Figure 4.5 shows some of the common

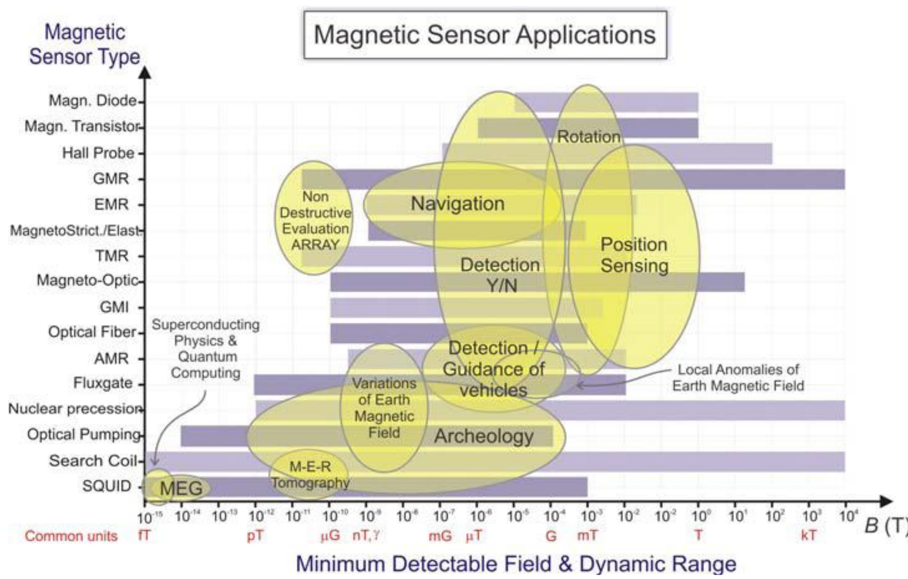


Figure 4.5: Magnetic sensing technologies: magnetic properties (minimum measurable field and dynamic ranges) and applications [93].

magnetic sensing technologies, and compares their magnetic characteristics in terms of minimum detectable field and dynamic range [93]. There are many factors other than sensitivity such as cost, frequency response, size, and power requirements that determine which sensor is best suited for an application [94]. Among these technologies, Hall Effect, anisotropic magneto-resistive (AMR), and magneto-inductive (MI) sensors are considered as good candidates for the TDS application because of their small size, high sensitivity, reasonable power consumption, and low cost.

The Hall Effect sensors operate based on Hall Effect, discovered by Edwin H. Hall more than 100 years ago. Hall Effect is a physical phenomenon that can be described as a small voltage (Hall voltage) is generated across an electrical conductor, transverse to an electric current in the conductor when a magnetic field is presented perpendicular to the current [96]. The commercial off-the-shelf (COTS) Hall Effect sensors contain the sensor element as described above plus a high gain integrated circuit (IC) amplifier in a single package. Some sensors also include an on-chip analog-to-digital converter (ADC) and a digital interface to directly communicate with an external microcontroller. Hall Effect sensors are low cost and can operate across a wide range of temperature. However, the sensitivity of commercial silicon-based Hall Effect sensors is relatively low, usually in the range of 10^{-3} to 0.1 T [97]. Most COTS Hall Effect sensors are single or dual axes, and can only measure magnetic field components that are perpendicular to their sensitive surfaces. Only one tri-axial Hall Effect sensor is available from Melexis (MLX90333) [98]. However, this sensor only provides computed angular information instead of raw magnetic field in its outputs. Hall Effect sensors are also available at Allegro Microsystem Inc.

Anisotropic magneto-resistive (AMR) sensor is based on the magneto-resistive effect in ferromagnetic metals that was first discovered by William Thompson and Lord Kelvin in 1856 [99]. The sensor is made of a nickel-iron (Permalloy) thin film deposited on a silicon wafer and is patterned as a resistive strip. The properties of the AMR thin film result in resistance change by 2-3% in the presence of the magnetic field. Typically, four of these resistors are connected in a Wheatstone bridge configuration so that both magnitude and direction of a field along a single axis can be measured [100]. AMR sensor typically has large bandwidth (1-5 MHz), since the reaction of the magneto-resistive effect is very fast and not limited by coils or oscillating frequencies. A typical measurable field of AMR sensor is in the range of 1 to 5000 μT with open-loop read out circuitry. With closed-loop feedback readout electronic methods, the minimum detectable field can be reduced to 0.1 nT for limited bandwidth [97]. One of the concerns for AMR sensor is that the sensor becomes saturated when it is exposed to a strong disturbing magnetic field, and as a result the performance of the sensor degrades in terms of both sensitivity and linearity. A short and high current set/reset pulse is needed to recover the sensor properties. This requires extra set/reset circuitry and increases the size and cost of the system. Another drawback of AMR sensors is that they are highly temperature dependent. Thus, while they can operate over a huge temperature range, their temperature sensitivity coefficients can be as high as 0.1 %/℃ [93]. AMR sensors are available from Philips, HL Planar, and Honeywell [101].

Magneto-inductive (MI) sensors are relatively new with the first patent issued in 1989 [102]. The sensor incorporates a solenoidal-geometry coil wrapped around a high-permeability magnetic core, which inductance changes with the applied external magnetic field. In the readout circuitry, the sense coil is the inductance element in a L/R relaxation oscillator, which varies the oscillation frequency proportional to the change of the coil inductance. By measuring the time to complete a fixed number of oscillations (periods), it is possible to derive the strength of the applied magnetic field [103]. The observed frequency shift can be as much as 100% as the sensor is rotated 90 degrees from the applied magnetic field [100]. The measurable field of MI sensors is in the range of 10 to 1000 μT. These sensors are simple in design, low cost, and low power. However, they are relatively slow since the maximum sampling rate and resolution are inversely related. The commercial MI sensors are only available from Precision Navigation, Inc. (PNI, Santa Rosa, CA) and used in compass applications [104]. PNI does not provide integrated version of three axial MI sensors. Therefore, a discrete Z sensor ($2.1 \times 2.2 \times 6.0$ mm^3) has to be used with an on-chip 2-axial sensor module ($7 \times 7 \times 1.35$ mm^3) which results in much higher profile than other solutions. Table 4.2 summarizes some important specifications of the COTS 3-axis Hall Effect, AMR and MI sensors.

Table 4.2: Commercial Off-The-Shelf Magnetic Sensors

Magnetic Sensors	Full Range (uT)	Resolution (nT)	Sampling Rate (Hz)	Current (mA)	Size (mm^3)	Output
Hall Effect (MLX90330) [98]	±50000	N/A	5k	13.5	$6 \times 5 \times 1.6$	Angular Data Only
AMR (HMC1043) [101]	±600	12	5M	10	$3 \times 3 \times 1.4$	Analog
MI (MS2100 + SEN-S) [104]	±1100	55	< 100	5	$7 \times 7 \times 1.35$ $2.1 \times 2.2 \times 6$	Digital SPI

MI sensors have been used in eTDS prototype Gen-1 to Gen-4 for its high resolution and simplicity to interface at the cost of limited sampling rate (13 Hz). In eTDS Gen-1, a pair of 2-D PNI magnetic sensor modules was mounted symmetrically at right angle on a baseball helmet faceguard close to the user's cheeks (Figure 4.1a) [84]. Each module contains a pair of orthogonal sensors, resulting in one, one, and two sensors in the X, Y, and Z-axes with respect to the helmet coordinates, respectively. These two sensors measures the magnetic field variation around users' mouth resulted from the movement of the magnetic tracer on the tongue, while a 3-D magnetic sensor module is mounted on top of the helmet as a reference to measure ambient magnetic field. The reference compass output is used to predict and cancel out the interfering magnetic fields at the location of the main sensor modules. This interference cancellation technique will be explained in more details in section 4.4.1.

In eTDS Gen-2 to Gen-4, a pair of 3-axial MI sensor modules including one MS2100 2-D sensor (X-Y) and one discrete SEN-S sensor (Z), was mounted on the headset to measure the magnetic field around the mouth. These 3-axial sensor modules can measure magnetic field vector in three directions (X, Y, and Z) and therefore provide more information compared to their 2-D counterpart. The reference sensor module was no longer needed in this case since an efficient stereo differential noise cancellation algorithm was implemented to minimize the interference of external magnetic field (more details later in section 4.4.1). This significantly reduced the power consumption and simplified the system design.

In eTDS prototype Gen-5, four 3-axial HMC1043 AMR sensors were used to improve the sampling rate (up to 50 Hz) for fast tongue motion detection, and to increase the detection range with larger number of sensors. By carefully designing the interfacing circuitry and implementing a smart sensor duty cycling algorithm in microcontroller firmware, we were also able to reduce the power consumption and the physical size of the sensor modules. The trade-off was the slightly lower resolution, which was partially compensated by using more sensors as well as improving the sensor signal processing algorithms.

4.2.2 Wireless Control Unit

The main function of the wireless control unit is to read the magnetic sensor outputs, assemble them into data packets, and then wirelessly send them to a nearby smartphone or PC for further processing. The wireless control unit also includes power management circuitry to duty cycle the sensor modules to reduce the power consumption. Some simple data processing algorithm, such as adaptive sampling and standby mode switching, can be implemented in local control unit too. The emphasis of control unit circuit design is on the low power consumption, small form factor, and high reliability. So far, two different versions of wireless control units have been developed, one for early versions of eTDS (Gen-1 to Gen-4) utilizing a MSP430 microcontroller (Texas Instruments, Dallas, TX) as its main processor, and the other for eTDS Gen-5 with a system-on-chip (SoC)

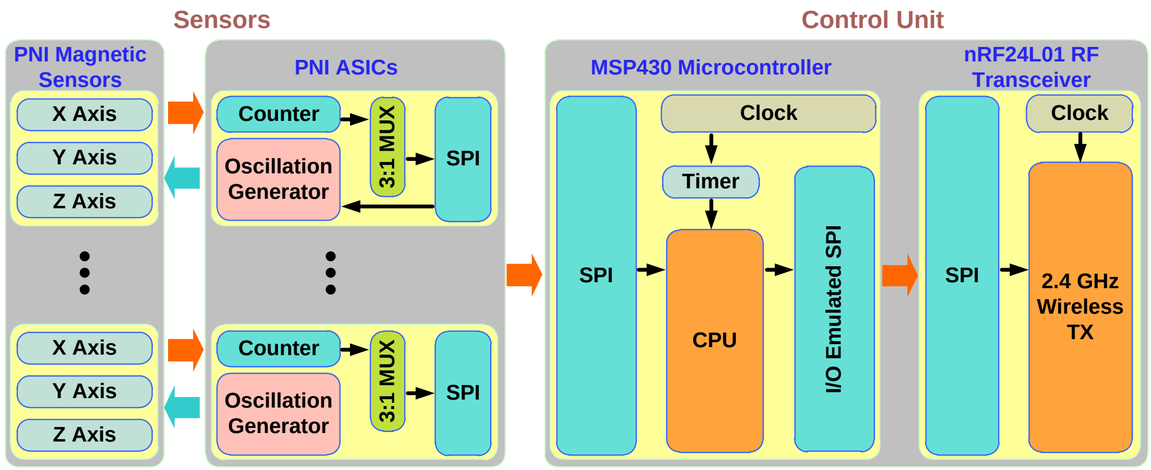


Figure 4.6: The block diagram of eTDS prototype Gen-4 wireless headset.

microcontroller CC2510 (Chipcon/Texas Instruments, Dallas, TX) as its core. The detailed architectures and the operational principles of these two control units will be presented separately in following sections.

Figure 4.6 shows the block diagram of the eTDS Gen-4 headset, an example of early eTDS prototypes. In this prototype, an ultra-low power MSP430F1232 microcontroller (MCU) is used to directly interface with two digital 3-axial MI sensor modules through serial peripheral interface (SPI). The MSP430 microcontroller takes 13 samples per second from each sensor through SPI, while activating only one sensor at a time to save power. After all sensors are read, their samples are packaged in one data frame, and sent to a 2.4 GHz ISM-band transceiver nRF24L01 (Nordic Semiconductor, Norway) through another SPI interface. The nRF24L01 transceiver assembles a wireless data packet by adding necessary preamble, network address and ID to the original data frame, and then wirelessly transmits it to a nearby PC. The nRF24L01 transceiver is turned on only when a wireless data frame is ready for transmission. Most of the time, the transceiver is in deep sleep mode, which only consumes ~3 uA current, to reduce the power consumption.

Table 4.3: External Tongue Drive System Gen-4 Specifications

Specification	Value
Control Unit	
Microcontroller	Texas Instruments - MSP430F1232
Sampling rate per sensor	13 Hz (operational), 1 Hz (standby)
Wireless transceiver	Nordic nRF24L01
Wireless band / data rate	2.4 GHz / 2.0 Mbps
Operating voltage / current	2.2 V / ~ 4 mA
Weight	5 gr without batteries
Magnetic Sensor Module	
Type	Magneto-inductive (PNI Corp., CA)
Sensor dimensions	MS2100 (X and Y): $7 \times 7 \times 1.5$ mm^3 SEN-S65 (Z): $6.3 \times 2.3 \times 2.2$ mm^3
Sensor module dimensions	$25 \times 23 \times 13$ mm^3
Resolution	MS2100: 0.026 μT, SEN-S65: 0.015 μT
Range	1100 μT
Sensitivity (programmable)	0.3 - 67 counts/μT
Weight	3 gr

Table 4.3 summarizes some important specifications of eTDS Gen-4 wireless headset.

In the latest version of eTDS Gen-5 headset, which diagram is shown in Figure 4.7, the differential output signals from each HMC1043 sensor bridge dedicated to each axis are multiplexed locally on the sensor module. Outputs from the two modules on each side (a total of four in this prototype) are further multiplexed on the control unit to yield a single time division multiplexed differential input voltage. The time division multiplexed signal is amplified by a low-power, low-noise, and high bandwidth instrumentation amplifier (INA), INA331 (TI, Dallas, TX), with a gain of 200 V/V. The high bandwidth of INA331 is favored to reduce the settling time of INA output after multiplexing. This can further reduce the system power consumption by shortening the sensor’s active time. The output of INA331 passes through a first-order RC low-pass filter (LPF) to limit the noise bandwidth before being sampled by a low power SoC MCU, containing a built-in analog-to-digital converter (ADC) and 2.4 GHz RF transceiver (CC2510, TI, Dallas, TX).

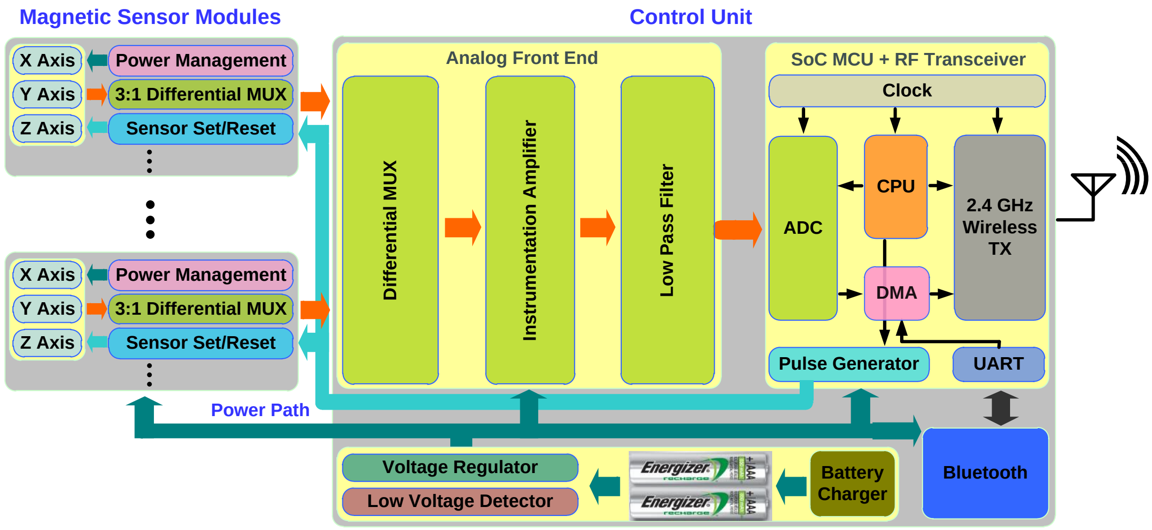


Figure 4.7: The block diagram of eTDS prototype Gen-5 wireless headset.

The CC2510's 12-bit on-chip delta-sigma ADC features much lower noise and therefore a higher effective number of bits (ENOBs) than the 12-bit successive-approximation-register (SAR) ADC available in most MSP430 MCUs. CC2510 samples each sensor output at 50 Hz, while turning on only one sensor at a time to save power. Each sensor is duty cycled at 2%, which results in a total duty cycle of 8% for all four sensor modules. To avoid sensor sensitivity and linearity degradation in the presence of strong fields (> 20 Gauss) when the magnetic tracer is very close to the sensor (< 1 cm), the MCU generates a sharp 2 μs pulse to reset the AMR sensors right before the differential sensor output is sampled.

The MCU always compares the left-back side module outputs with a predefined threshold value to check if the user has issued a standby/on command. This threshold is defined as the minimum sensor output when the magnetic tracer is held from the sensor at 1 cm distance. If users hold the tongue close to the left-back module (< 1 cm) for more than three seconds, the TDS status switches between operational and standby modes.

Table 4.4: External Tongue Drive System Gen-5 Specifications

Specification	Value
Control Unit	
Microcontroller	Texas Instruments – CC2510
Wireless transceiver	CC2510 built-in
Wireless band / data rate	2.42 GHz / 500 kbps
Number of sensors / duty cycle	4 / 8%
Sampling rate per sensor	50 Hz (operational), 1 Hz (standby)
Operating voltage / current	2.5 V / ~ 6.5 mA
Weight	14 gr without batteries
Magnetic Sensor Module	
Type	Honeywell HMC1043 Magneto-resistive sensor
Sensor dimensions	$3 \times 3 \times 1.5$ mm^3
Sensor module dimensions	$38 \times 6 \times 3$ mm^3
Resolution	0.012 μT
Sensitivity / Range	8 LSB/μT / ±600 μT
Weight	1.1 gr

When the system is in the operational mode, all four sensor outputs are sampled at 50 Hz, and the results are packed into the data frame that is ready for RF transmission. When the standby mode is activated, the MCU only samples the left-back side module axes at 1 Hz and turn off the RF transceiver to save power.

The power management circuitry includes a pair of AAA Ni-Mn batteries, a voltage regulator, a low-voltage detector, and a battery charger. The system consumes roughly 6.5 mA at 2.5 V supply, and can run for more than 120 hours following a full charge. Table 4.4 summarizes some of the key specifications of the eTDS Gen-5 wireless headset.

4.3 Wireless Receiver

Two types of wireless receiver prototypes have been built to interface eTDS headsets with both computers and powered wheelchairs (PWC).

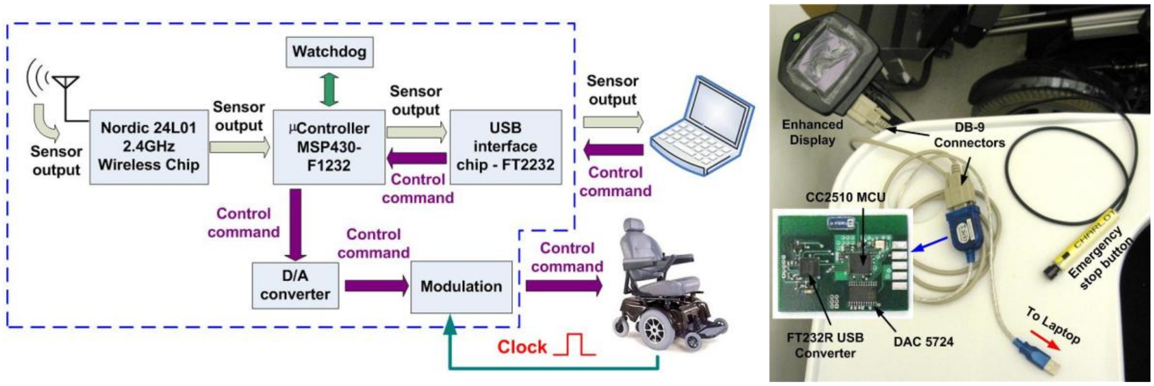
Figure 4.8: The wireless USB receiver dongle for eTDS prototype Gen-5.

4.3.1 USB Receiver

The first type of receiver is in the form of a USB dongle designed for computer access. Figure 4.8 shows a prototype of such receiver equipped with a USB port to communicate sensor data with a laptop.

In eTDS early generations, a MSP430 MCU and a low power transceiver nRF24L01 are used in the USB receiver to wirelessly receive the sensor data from the headset. The nRF24L01 is configured in RX mode and continuously checks for any incoming data packets. If a valid TDS data packet with matched network address and ID is detected, nRF24L01 will dissemble the packet, extract the payload, and save the sensor data in its local buffer. It then generates an interrupt request to notify the MSP430 that a valid wireless data packet is ready to read. The MSP430 communicates with nRF24L01 through SPI interface to read the TDS data packet and then sends the data to a laptop through USB connection for further processing.

In eTDS Gen-5, a SoC MCU CC2510 is used to substitute the combination of MSP430 and nRF24L01 in previous generations, resulting in a more compact design. Similarly, the CC2510 MCU wirelessly receives the sensor data from the eTDS headset



(a) (b)

Figure 4.9: TDS-wheelchair interfaces: (a) Block diagram and signal flow graph of the TDS-PWC interface version 1 to substitute VR2 joystick controller used in the low-end commercial PWCs, and (b) TDS-PWC interface version 2 connecting a laptop to a PWC controller, available in most advanced PWCs, via USB and standard DB-9 connectors, respectively.

and delivers them to a PC through USB. The communication between the CC2510 and the computer is via a RS-232 serial port, while a FT232R serial-to-USB converter changes the physical form of the connector in to USB.

4.3.2 Powered Wheelchair Controller

The second type of wireless receiver is the TDS-wheelchair (TDS-PWC) controller, which is designed to control PWCs through a laptop. The TDS-PWC interface is attached to a laptop via USB and communicates with the eTDS headset using the same mechanism as the USB receiver. In addition, the TDS-PWC controller receives the control commands from the laptop and provides multiple channels of analog output signals to control a PWC.

Two TDS-PWC controller modules have been developed to operate PWCs from different vendors. The first module is built to substitute a VR2 joystick controller from PG Drives Technology, which is widely used in the low-end commercial PWCs from Quantum, Pride, Golden Technology, etc. Figure 4.9a shows the block diagram and signal flow graph of this control module. eTDS control commands, once detected from the sensors data, are sent from the laptop to a microcontroller (MSP430) in the interface module to determine the amplitudes of the PWC control signals through 12-bit digital-to-analog converters (DAC). These DC levels are chopped by an analog switch to be synchronized with the VR2 controller master clock before substituting its joystick input signals. The lower amplitudes of chopped signals change between 0 and 5 V, and upper levels always stay at 5 V. The direction and speed of the two PWC electric motors can smoothly be controlled by changing the lower amplitudes of these signals [109].

Alternatively, some advanced wheelchairs such as C500 (Permobil, Lebanon, TN) and Q6000 (Pride Mobility, Exeter, PA), are equipped with special wheelchair control units which can receive control signals from alternative controllers through a standard DB9 interface [110], [111]. The compatible signals for such control units are a set of DC analog voltage levels in the range of 4.8 ~ 7.2 V without chopping or synchronization. The second control module (shown in Figure 4.9b) generates these signals using a microcontroller (MSP430 or CC2510) and a12-bit DAC. During the normal operation, data packets that are wirelessly sent by the TDS headset are received by the PWC controller and sent to a laptop through USB for further sensor data extraction and processing. The SSP algorithm running on the laptop interprets the commands issued by the users based on the received sensor data. These commands are used to modify the speed and rotation vectors that are associated with the PWC's linear speed and rotation rate. State vectors are then sent from the laptop to the TDS-PWC receiver to be converted to multichannel analog signals that are compatible with the PWC universal controller using an off-chip DAC, AD5724 (Analog Device, Norwood, MA), driven by the the microcontroller. These analog signals that are in the range of 4.8 – 7.2 V are applied to the PWC universal control unit through its DB-9 connector to control the wheelchair movements.

To improve safety, a watchdog timer is added to both TDS-PWC interfaces. If the wireless link is broken due to a malfunction in the eTDS or electromagnetic interference, or if the laptop freezes, the slowdown in receiving control commands is detected by the watchdog. In this case, the microcontroller will reset all control signals to bring the PWC to standstill. It will not respond to any new incoming control commands until a normal command rate is resumed.

4.4 Sensor Signal Processing Algorithm

The main function of sensor signal processing (SSP) algorithm is to process the magnetic sensor outputs, and extract specific tongue commands based on the pattern of magnetic field variations. The SSP algorithm is developed in the MATLAB environment, compiled in to C DLL library, and then embedded in the LabVIEW GUIs for real time command detection. The algorithm has three major components: external magnetic interference (EMI) cancellation, feature extraction (FE), and command classification. The EMI cancellation is a data pre-process procedure to clean up the sensor output and enhance the signal-to-noise ratio (SNR) by eliminating the interference from the ambient magnetic field. The FE component is used to extract the most important features from the magnetic sensor data, while the command classification interprets the data as different commands based on the correlation between the extracted features and a set of predefined features.

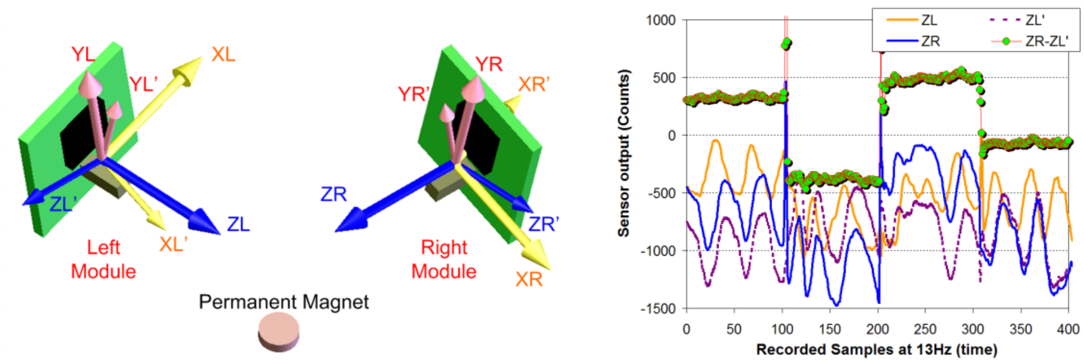
4.4.1 External Magnetic Interference Cancellation

Due to their high sensitivity, magnetic sensors are inevitably affected by the EMI such as the earth magnetic field (EMF). This results in a poor SNR at the sensor outputs, which degrades the performance of the SSP algorithm. Therefore, eliminating the EMI is necessary to enhance the TDS performance, and reduce the probability of errors in command interpretation. Two different methods were implemented to solve this problem: (1) using a reference electronic compass [84], and (2) using a stereo differential cancellation algorithm [86].

In eTDS Gen-1, a 3-axis electronic compass module was used as a reference to minimize the effects of EMI. The reference compass was placed on top of the helmet (see Figure 4.1a) to be far from the tongue magnet and only measure the ambient magnetic field. The reference compass output was then used to predict and cancel out the interfering magnetic field at the location of the main sensor modules [84]. This method is straightforward and easy to implement. However, adding extra reference electronic compass increases the size of the TDS and more importantly it burns more power. In addition, this method becomes less effective when the EMF around reference compass is disturbed by nearby metal objects or active magnetic sources, such as computer monitors or speakers.

Alternatively, a differential magnetic field measurement technique was proposed and proved to be inherently robust against EMI. In this method, the outputs of each 3-axial sensor module are transformed, as if the sensor was oriented in parallel to the opposite module, and subtracted from those outputs. As a result, the common-mode components in the sensor outputs, which are mainly resulted from the EMI, are cancelled out, while the differential-mode components, mainly resulted from the movements of the local magnetic tracer, are retained and even magnified [86].

Figure 4.10a depicts the relative position and orientation of the 3-axial sensor modules



(a) (b)

Figure 4.10: (a) Relative 3-D position and orientation of the bilateral 3-axis sensor modules and the permanent magnetic tracer attached to the user's tongue. (b) Original, transformed, and differential outputs of the Z-axis sensors when the subject issues two LEFT commands while walking in the lab.

and the magnetic tracer attached to the user's tongue, where X_L, Y_L and Z_L are the three axes of the left module, and X_R, Y_R and Z_R are those of the right one. Since the relative position and orientation of the two modules are known, each module can be mathematically rotated to create a virtual module at the same location but parallel to the module on the opposite side using coordinate transformation theory [105]. The linear relationship between the original and the virtual rotated modules can be expressed in the matrix form:

$$\begin{cases} X_L^{'} = a_{xL}X_L + b_{xL}Y_L + c_{xL}Z_L + d_{xL} \\ Y_L^{'} = a_{yL}X_L + b_{yL}Y_L + c_{yL}Z_L + d_{yL} \\ Z_L^{'} = a_{zL}X_L + b_{zL}Y_L + c_{zL}Z_L + d_{zL} \end{cases} \tag{4.2}$$

where *a*, *b*, *c* and d are the linear coefficients, which indicate the relative orientation and gain differences between the two sensor modules. These coefficients can be found using multi-linear regression algorithm [106].

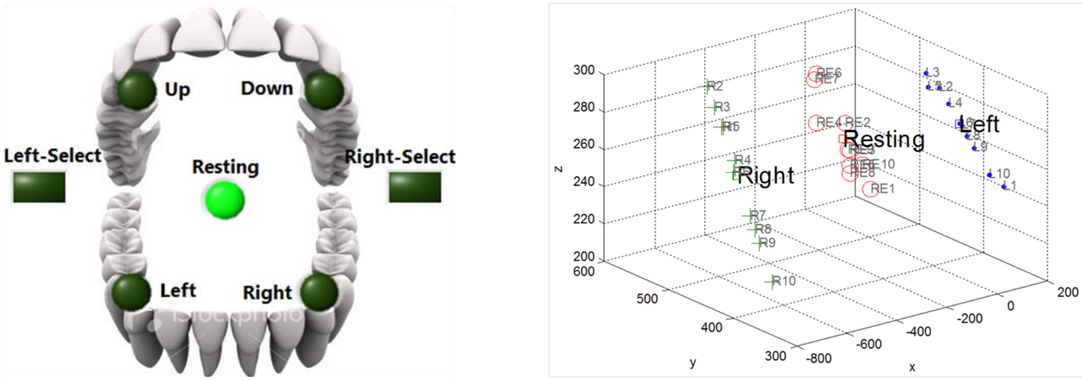
Once the linear relationship between the two modules is setup, any source of EMI, which is usually far from the sensors, will result in equal outputs among each module and its virtual replica on the opposite side. On the other hand, the two module outputs resulted from the movements of the strong nearby magnetic tracer would be quite different unless the magnet moves symmetrically along the sagittal plane. Therefore, if the outputs of each sensor are subtracted from its associated virtual sensor on the opposite side, the EMI components will be canceled out or significantly diminished, while the tracer components are likely to be amplified. As a result, the effects of EMI will be minimized and the SNR will be greatly improved [87].

Figure 4.10b shows the output waveforms of the Z_L and Z_R sensors on the left and right module when the user, wearing the TDS prototype, issues two "left" commands while walking in the lab. This figure also shows the transformed output, Z_L', and the differential signal, $Z_R - Z_L'$, which is much cleaner than the two original raw signals.

4.4.2 Feature Extraction

The feature exaction (FE) algorithm, which is based on principal component analysis (PCA), is used to reduce the dimensions of the incoming sensor data and accelerate computations [107].

During the feature identification (or training) session, the user associates a preferred tongue movement or position to each TDS command, and repeats that command for 10 times in 3-second intervals by moving his/her tongue from its resting position to the desired position after receiving a visual cue from a GUI (see Figure 4.11a). A total of 18 samples (3 per sensor) are collected in an 18-variable vector in each repetition, and labeled with the executed command. The FE algorithm calculates the eigenvectors and eigenvalues of the covariance matrix that consists of the training 18-variable vectors, offline. Three eigenvectors (*v1, v2, v3*) with the largest eigenvalues are then chosen to construct the PCA feature matrix, V = [*v1, v2, v3*]. This is equivalent to extracting the



(a) (b)

Figure 4.11: (a) The visual presentation of tongue commands on a mouth model, indicating the positions that user should hold their tongue to train different commands. (b) The extracted PCA feature space containing Left, Right and Resting commands.

most significant features of the sensor output waveforms for each specific command in order to reduce the dimensions of the incoming data from 18 to 3. The labeled samples are then used to form a cluster in the 3-D feature space for each command. An example of extracted feature space containing Left, Right and Resting commands, is shown in Figure 4.11b.

During the normal TDS operation, 3 consecutive samples at any time from each of the 6 individual sensors are used to construct the 18-variable incoming raw sensor vectors, M_0, which are then reflected onto the 3-D feature space using

$$M = V^T \bullet M_0 \tag{4.3}$$

where M is the 3×1 principal components vector. These 3-variable vectors, which are easier to classify, still contain the most significant features that help discriminating them from other commands when they are being reflected onto the virtual 3-D feature space.

4.4.3 Command Classification

K-nearest neighbors (KNN) classifier is used within the feature space to evaluate the proximity of the incoming data points to the clusters formed during the training session.

The KNN algorithm starts at an incoming data point and inflates a virtual sphere until it contains K nearest training points. Then it associates the new data point to the command that has the majority of the training points inside the sphere [108]. With these SSP algorithms, the TDS prototype can recognize up to six different tongue commands along with a neutral command, which is automatically issued when the tongue is at its resting position.

4.5 Graphical User Interface (GUI)

A graphical user interface (GUI) is an important bridge connecting the users and the target devices under control. A well designed GUI can not only facilitate the learning process of setting up and using the system, but also has the potential to maximize users' efficiency and minimize the fatigue during the operation. We have developed dedicated user-friendly GUIs to allow users to both use computers and drive PWC.

4.5.1 Computer Access GUI

The main function of TDS in computer access is to substitute the mouse function by controlling the cursor movements using tongue commands. In other words, the system can be used with any computer software that is normally accessible by a regular mouse as long as the TDS SSP is running in the background to detect user's commands. Therefore, the only GUIs needed for computer access are those allow user to define their own tongue commands during the command training stage, which is a critical step before users actually start using the system.

<u>a) Pre-training GUI:</u> This GUI was designed to help users to identify their desired tongue positions for each command using a 3-D tongue position representation, shown in Figure 4.12. This GUI shows the current (trace of green stars) and previous (other

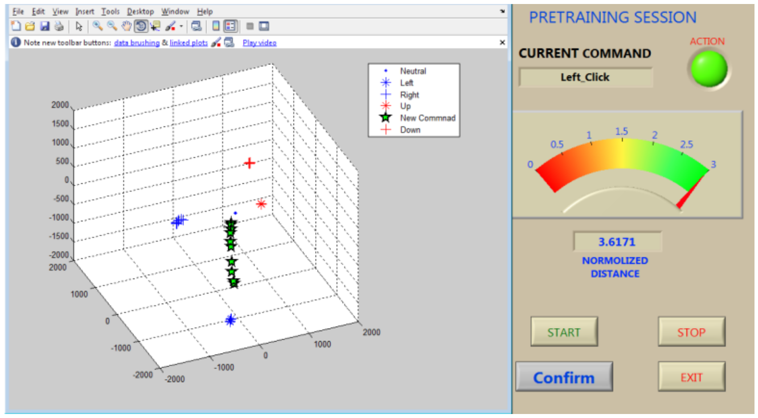


Figure 4.12: Pre-training session GUI showing the 3-D representation of the current (trace of green stars) and previous (other markers) tongue positions for different TDS commands. The normalized minimum distance between current tongue position and all previous positions is shown by a dial on the right. Users should define their tongue positions for TDS commands in a way that markers of different commands are separated from each other and the dial stays in the green zone.

markers) tongue positions associated to different commands by a 3-D vector that is derived from the two 3-axial sensor outputs after the earth magnetic field cancellation. Users should define their tongue positions for the TDS commands in a way that markers of different commands are well separated from each other. The gauge on the right reflects in real time the distance between the current tongue position and the closest previously defined command position (l_{min}) onto three zones, which are color coded. Users should define each new command such that the gauge will stay within the green zone, which means that the new command is far enough from all other previously defined commands. The operator can confirm the current command definition by clicking on the CONFIRM button on the bottom right of the GUI.

<u>b) Training GUI:</u> This GUI allows the user to train arbitrary number (from 1 to 7) of tongue commands, which positions have been properly indicated using the pre-training GUI. It also provides the operator with an interactive tool to refine the training results by manually selecting and removing the outcast training points. The GUI presented to the

(a) (b) (c)

Figure 4.13: (a) The TDS training data of four tongue commands plus resting, individually marked and projected on to a 3-D PCA space. (b) The table in the training GUI, in which each button is associated with one training point in the PCA space with a command name (columns) and an index number (rows). This table allows the operator to identify and remove the outcast training points. (c) TDS command clusters in the 3-D PCA space after the outcast training point in (a) for the "Down" command is removed.

users during training is shown in Figure 4.11a. The GUI prompts the users to execute each command by turning on its associated indicator on the screen in 3 s intervals. The users should issue the command by moving their tongue from its resting position to the corresponding command position when the command light is on, and returning it back to its resting position when the light goes off. This procedure is repeated 10 times for the entire set of 7 commands including the tongue resting position. At the end of this process, the training results are presented in the 3-D PCA space as individually marked TDS command clusters, shown in Figure 4.13a. At this point, the operator is provided with a training table, Figure 4.13b, right beside the PCA space. In this table, each button is associated with one of the training points in the PCA space, with a command name (columns) and an index number (rows). The training table allows the operator to identify the outcast training points and manually remove them by selecting their corresponding buttons, and clicking on the "Remove" button. Figure 4.13c shows the TDS command clusters in the 3-D PCA space after the outcast training point in Figure 4.13a for the

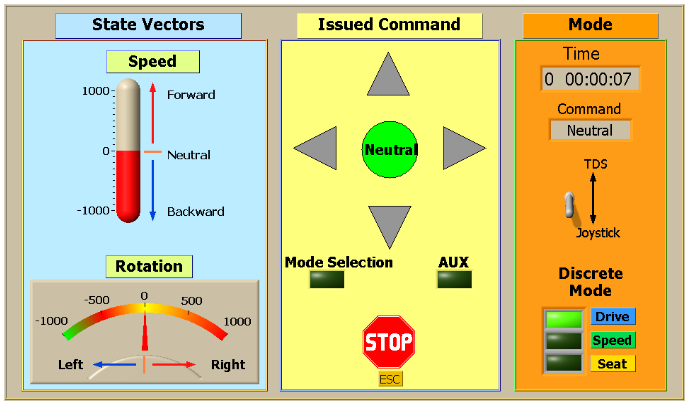


Figure 4.14: The PWC control GUI provides users with visual feedback on the commands that have been selected as well as the wheelchair driving status.

"Down" command is removed.

4.5.2 Powered Wheelchair Control GUI

In the PWC GUI, a universal wheelchair control protocol has been implemented based on two state vectors, shown on the left column of Figure 4.14: one for linear movements and one for rotations [85]. The speed and direction of the wheelchair movements or rotations are proportional to the absolute values and polarities of these two state vectors, respectively. Five commands are defined in the eTDS GUI to modify the analog state vectors, resulting in the wheelchair moving forward (FD) or backward (BD), turning right (TR) or left (TL), and stopping/neutral (N), which are indicated in the central column of Figure 4.14. Each command increments/decrements its associated state vector by a certain amount until a predefined maximum/minimum level is reached. For example if the user keeps issuing the FD command, the linear motion state vector increases and the PWC accelerates in the forward direction until it reaches a predefined maximum speed. Based on these fundamental rules, several control strategies are implemented as following [88].

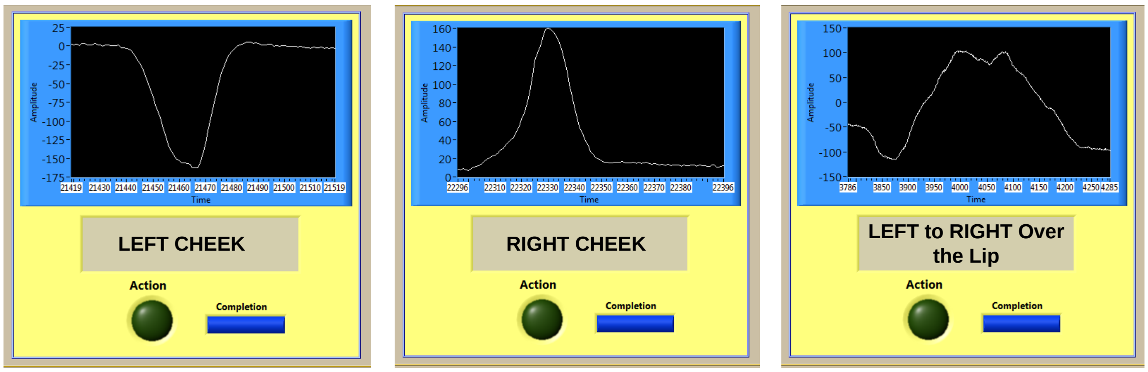
a) Discrete control: In this strategy, the state vectors are mutually exclusive, i.e. only one state vector can be nonzero at any time. If a new command changes the current state, e.g. from FD to TR, the old state vector (linear) has to be gradually reduced/increased to zero before the new vector (rotation) can be changed. Hence, the user is not allowed to change the moving direction of the wheelchair before stopping. This was a safety feature particularly for novice users at the cost of reducing the wheelchair agility. In this strategy, the N command, which is issued automatically when the tongue returns back to its resting position, linearly returns all state vectors back to zero. Therefore, by simply returning the tongue to its resting position, the user can bring the PWC to a standstill.

b) Continuous control (unlatched control): This strategy uses the same command definitions as discrete control in (a). However, the state vectors are no longer mutually exclusive, which means that the users are allowed to steer the PWC to the left or right as it is moving forward or backward by directly moving their tongues from FD/BD to TL /TR position. Therefore, the PWC movements are continuous and much smoother, making it possible to follow a curve. This strategy is also named as “unlatched control” because the subjects need to hold their tongues in the command positions (FD and BD) in order to maintain and increase the wheelchair speed. The wheelchair stops moving when the tongue is returned to the resting or neutral command position.

c) Latched control: This strategy uses the same directional TDS commands as the continuous (unlatched) control mode. The difference between this strategy and the unlatched mode is that the wheelchair speed is locked so that the tongue can return to its resting position, while the wheelchair maintains its speed. The wheelchair speed is divided into the following five levels: B, N, F1, F2 and F3. F3 offers the fastest forward movement speed among all F (FORWARD) levels. The speed of B (BACKWARD) is always the same as F1. By quickly touching the tongue to the FD command position, the subject can increase the speed by one level in this order: B→N→F1→F2→F3. A quick touch of the BD command leads to a speed decrease by one level (F3→F2→F1→N→B). Regardless of the speed level, issuing BD command for 1 sec bring the PWC to an emergency stop.

d) Gear-shift control: In this strategy, by employing an additional TDS command, users are able to shift the gear to operate the PWC at a different speed by setting a different maximum level for the linear state vector. By issuing the 6th command for 1 s, the user can shift the gear from N→1→2→3→R→N (N- neutral, 1- lowest speed gear, 2- medium speed gear, 3- highest speed gear, R- reverse gear). For safety reasons, the user has to stop the PWC before shifting gears. Since a reverse gear is already included in the gear box in this strategy, the (FD, BD) functions in (a) and (b) have changed to acceleration and deceleration. When users issue an FD command, the PWC speeds up to a maximum value depending on which gear is selected. If Reverse gear is selected, the maximum speed is always set to gear 1, and the FD command increases the backup speed. Similarly, the BD command decreases the PWC speed regardless of the direction of motion. The N command does not affect the linear state vector but it decreases the rotation state vector to zero.

e) Semi-proportional control: This strategy also has five different speed levels: B, N, F1, F2 and F3, similar to the latched control mode. Switching between different levels is processed by quickly touching the tongue to the cheeks. A quick touch to the left cheek increases the speed level by one step, while a quick touch to right cheek changes the speed level in the opposite direction. The speed is also “latched” in this mode, which means a subject can rest the tongue in the middle while the wheelchair maintains its



(a) (b) (c)

Figure 4.15: The GUIs for the semi-proportional control strategy calibration: (a) Quickly touch the left cheek with the tip of the tongue to define FORWARD command, (b) Quickly touch the right cheek with the tip of the tongue to define BACKWARD command, and (c) Slowly move the tongue between the left and right edges of the lips over the lower lip to determine the range of continuous tongue movement for steering.

speed. The movement of the tongue over the lips changes the direction of the wheelchair. The rotation rate is proportional to the distance between the magnetic tracer and the sensors. Therefore, the closer the tongue is to one edge of the mouth, the faster the wheelchair rotates in that direction, thus termed the semi-proportional control strategy. Two consecutive quick touches to the right cheek are defined as an emergency stop command and will bring the wheelchair to an instant standstill.

None of the discrete TDS commands are used in the semi-proportional control strategy. Instead, a simple calibration process is utilized to define the thresholds for detecting tongue touches to the left and right cheeks, and to measure the range of sensor outputs as a result of continuous tongue movements over the lips to define the wheelchair rotation rate. Figure 4.15 shows the Calibration GUI, which is divided into three phases. *Phase 1*: Quickly (within two seconds) touch the left cheek with the tip of the tongue once the green action light is on. This action is repeated three times and the system uses 50% of the averaged peak value as the threshold for left cheek touch. *Phase 2*: Quickly (within two seconds) touch the right cheek with the tip of the tongue after the green action light is on. The action is repeated three times and the system uses 50% of the averaged peak value as the threshold for right cheek touch. *Phase 3*: Slowly move the tongue between the left and right edges of the lips over the lower lip to determine the range of continuous tongue movement, on which the maximum wheelchair rotation rate is defined. Subjects start the movement as soon as the green action light is on. The movement is repeated several times within the 15 seconds recording window.

4.6 Summary

In this chapter, we have presented the design and development of external Tongue Drive System (eTDS) prototypes, which all consist of following major components: 1) A small permanent magnet attached to user's tongue and used as a tracer; 2) A wireless headset containing a group of magnetic sensors to capture tongue motion, and a low power wireless control unit to read and wireless transmit the sensor samples; 3) A wireless receiver that receives the sensor data and delivers them to a PC for further processing; 4) Graphical user interface running on the PC with embedded signal processing algorithm to process the sensor data and recognize the tongue commands. The selection and design of each component are described in details. The focus of the hardware development is on the size, power consumption and the reliability of the wireless communication; while the computation efficiency, ease to use, and intuitiveness are the primary concerns in software (GUI and SSP) design. The performance evaluation of these prototypes by both able bodied subjects as well as patients with high level SCIs will be presented in following chapters.

CHAPTER V

ABLE-BODIED HUMAN TRIALS

Extensive evaluation of any new assistive technology is a key component of scientific research in this field, and the best way to guide the technical design and development cycle in the right direction [91]. We have conducted several rounds of human subject trials on the eTDS with both able-bodied subjects [84], [88] as well as those with high level spinal cord injuries (C2-C5) [90]. In this chapter, we report the experiment setups and the results of single-session able-bodied human trials. During these trials, healthy subjects, recruited from undergraduate and graduate student population, were asked to wear the eTDS headset and perform a set of experiments to measure the performance of eTDS in both computer access (CA) and powered wheelchair navigation (PWCN). CA and PWCN sessions were conducted by two groups of subjects at different experiment sites using eTDS prototype Gen-2 (Figure 4.1b) and Gen-3 (Figure 4.1c) respectively.

5.1 Subjects

The computer access (CA) session of the able-bodies human trials was completed at North Carolina State University (NCSU) using eTDS prototype Gen-2. Six able-bodied human subjects were recruited from the engineering graduate student population of the NCSU, comprising of two females and four males with ages from 23 to 34 years old. The PWC navigation (PWCN) session was conducted at Georgia Institute of Technology (GaTech) with eTDS prototype Gen-3. Twelve able-bodied human subjects were recruited from the GaTech graduate student population, comprising of ten males and two females with ages from 23 to 35 years old. In both populations, one of the subjects (subject-A) was a member of the research team and quite familiar with the TDS. However, he was not a TDS user on a daily basis. The trials were approved by both the NCSU and GaTech institutional review board (IRB), and the informed consent was obtained from each subject prior to the trials.

5.2 Experimental Procedure

5.2.1 Magnet Attachment

A new permanent magnet was disinfected using 70% isopropyl rubbing alcohol, dried, and attached to the subjects' tongue, about 1 cm from the tip, using cyanoacrylic tissue adhesives (Cyanodent, Ellman Intl. Inc., Oceanside, NY). The subjects then wore the eTDS prototype, and were allowed to familiarize themselves with the eTDS and magnetic tracer on their tongue for up to 15 minutes.

5.2.2 Command Definition

To facilitate command classification, the subjects were advised to choose their tongue positions for different commands as diversely as possible. They were also asked to refrain from defining the TDS commands in the midline of the mouth (sagittal plane) because those positions are often shared with the tongue natural movements during speech, breathing, and coughing. Our recommended tongue positions were as follows: touching the roots of the lower-left teeth with the tip of the tongue for "Left", lower-right teeth for "Right", upper-left teeth for "Up", upper-right teeth for "Down", left cheek for "Left click", and right cheek for "Double click".

During command definition, the subjects were presented with a pre-training GUI shown in Figure 4.12, and asked to search for proper tongue positions for different commands. They were instructed to define each new command such that the gauge would stay within the green zone, which meant that the new command was far enough from all other previously defined commands [87]. The command positions were then saved and practiced for a few times to make sure that the subjects had learnt and memorized all tongue positions.

5.2.3 Training Session

During this session, the GUI (Figure 4.11a) prompted the subject to execute each command by turning on its associated indicator on the screen in 3 s intervals. The subjects were asked to issue the command by moving their tongue from its resting position to the corresponding command position when the command light was on, and returning it back to its resting position when the light went off. This procedure was repeated 10 times for the entire set of 6 commands plus the tongue resting position, resulting in a total of 70 trial data points.

5.2.4 Computer Access Session

A) CA-1 Response Time Measurement: This experiment was designed to provide a quantitative measure of the TDS performance by measuring how quickly and accurately a command can be issued from the time it is intended by the user. This time, which is referred to as the TDS response time *T*, along with the probability that a correct command can be issued within *T*, were used to calculate the information transfer rate (*ITR*) for TDS, which is a widely accepted measure for evaluating and comparing the performance of different BCIs. The *ITR* indicates the amount of information that is communicated between a user and a computer within a certain time period. It has been originally derived from the Shannon's information theory, and further summarized by Pierce [112], [113]. There are various definitions for the *ITR* [114]. However, we have used the definition by

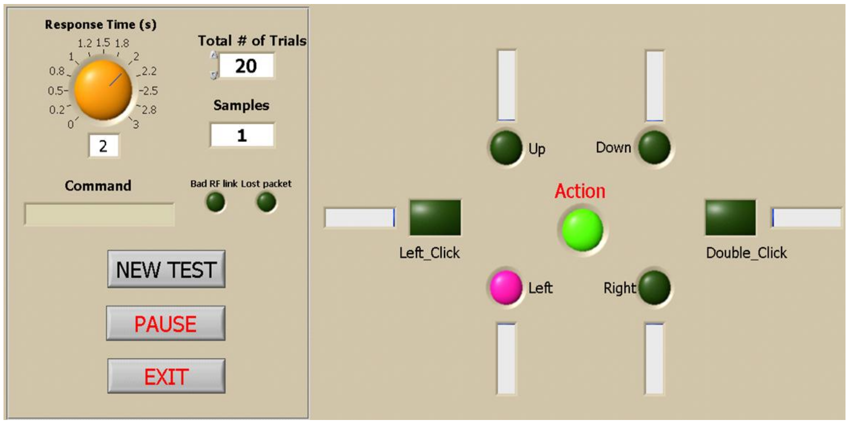


Figure 5.1: The Graphical User Interface (GUI) for TDS response time measurement.

Wolpaw [61], [115].

$$ITR = \frac{1}{T}\left(\log_2 N + P\log_2 P + (1-P)\log_2 \frac{1-P}{N-1}\right) \qquad (5.1)$$

where N is the number of individual commands that the system can issue, T is the system response time in minutes, and P is the mean probability that a correct command is issued within a specific time period, T.

A dedicated GUI (Figure 5.1) was developed for this experiment to randomly select one out of 6 direct commands and turn its indicator on. The subjects were asked to issue the indicated command within a specified time period, T, on an audio-visual cue [89]. The GUI also provided the subjects with a real time visual feedback by changing the size of a bar associated to each command, indicating how close the tongue was to the position of that specific command. T was changed from 2 s to 1.5, 1.0, 0.8, and 0.6 s, and 40 commands were issued each time. The mean probability of correct choices (*PCC*) for each T was recorded.

<u>B) CA-2 Maze Navigation:</u> The purpose of this experiment was to examine the eTDS performance in navigation tasks, such as controlling a PWC, in a controlled and safe environment. Subjects were required to navigate the mouse cursor within a maze from a

starting point by issuing a double-click (start command) to a stopping point with a single-click (stop command), while the GUI was recording the cursor path and the elapsed time, *ET*. The cursor was driven by the discrete commands in an unlatched mode, which required the subjects to hold their tongue at the position defined for a specific direction to continue moving the cursor. To achieve finer control, the cursor started moving slowly, and gradually accelerated if the users held their tongue in the same position, until it reached a certain velocity. The maze was designed to force the users utilize all eTDS commands. Every subject repeated this task four times and the average *ET* was calculated.

5.2.5 Powered Wheelchair Navigation Session

At the beginning of powered wheelchair navigation (PWCN) session, the subjects were required to complete a sensor calibration step to obtain the linear regression coefficients for the stereo differential SSP algorithm that cancels out the EMF interference. This step was particularly important for PWC session since the EMF interference had a huge impact on the sensors outputs when the sensors moved and rotated with the PWC during the experiment. The calibration should be taken before attaching the magnetic tracer to the subject's tongue, because the recorded data should only include the external magnetic field. Subjects wore the eTDS prototype headset, and were asked to move around in the experimental room, while the GUI recorded 1000 data points. The calibration coefficients were then calculated and saved for the following steps.

Then, the subjects were asked to go through magnet attachment, command definition and training steps as the computer access session to define and train six TDS commands. After familiarizing themselves by navigating the mouse cursor in a virtual environment as

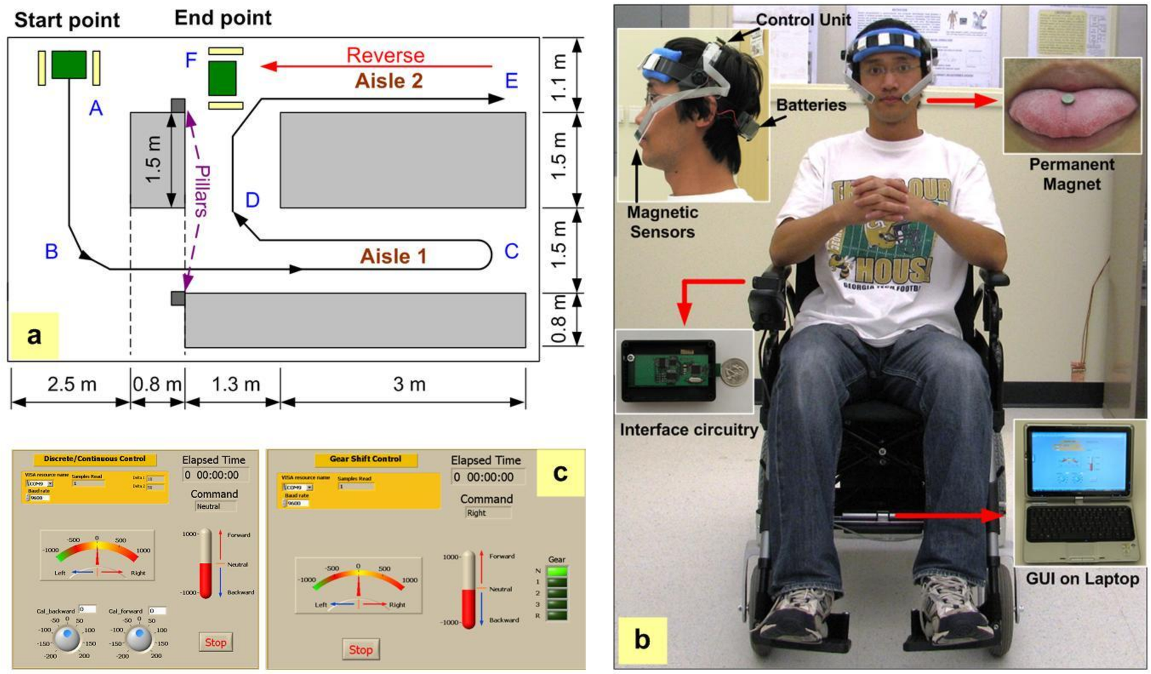
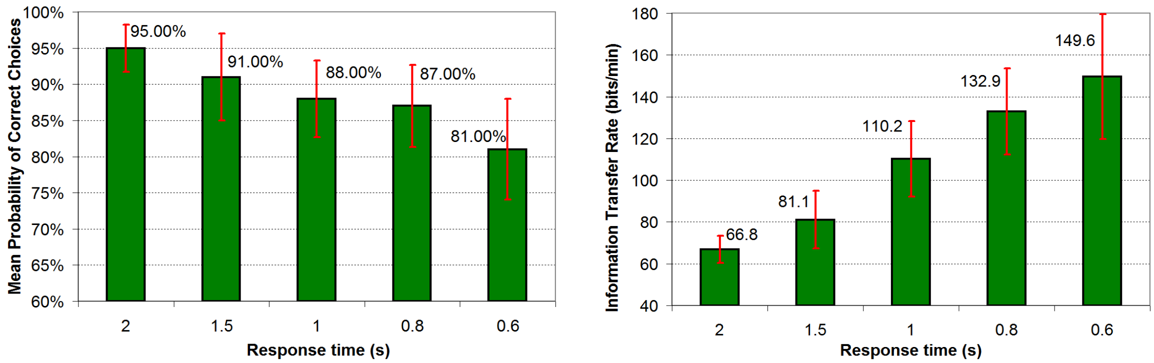


Figure 5.2: Experiment setup of PWC navigation human trials by able-bodied subjects: (a) Plan of the obstacle course showing the dimensions and approximate PWC trajectory, (b) eTDS prototype Gen-3 worn by an able-bodied subject to wirelessly control a PWC, and (c) The GUIs for the TDS-PWC control developed in LabVIEW environment.

that described in section 5.2.4b, and test-driving the PWC with TDS for ~10 min, the subjects were required to drive the PWC with their tongue through an obstacle course, shown in Figure 5.2a. The track was designed to require the subjects to use all TDS control commands, and perform various navigation tasks such as making a U-turn, back up, and fine tune the PWC orientation in a limited space, while moving forward or backward. The maximum PWC speed and rotation rates were set to 0.5 m/s and 36 degree/s, respectively, and the acceleration/deceleration rates were set to 0.125/-0.5 m/s^2. Figure 5.2b shows one of the subjects sitting on the PWC with his hands crossed, which is the position he was asked to maintain throughout the experiments.

During the experiment, the laptop was either placed in front of the subjects to provide them with visual feedback (VF) as in Figure 5.2c or hidden beneath the seat. The subjects



(a) (b)

Figure 5.3: Test results of response time measurement by five able-bodied subjects: (a) The mean probability of correct choice (PCC) vs. the eTDS response time, and (b) The eTDS information transfer rate vs. response time.

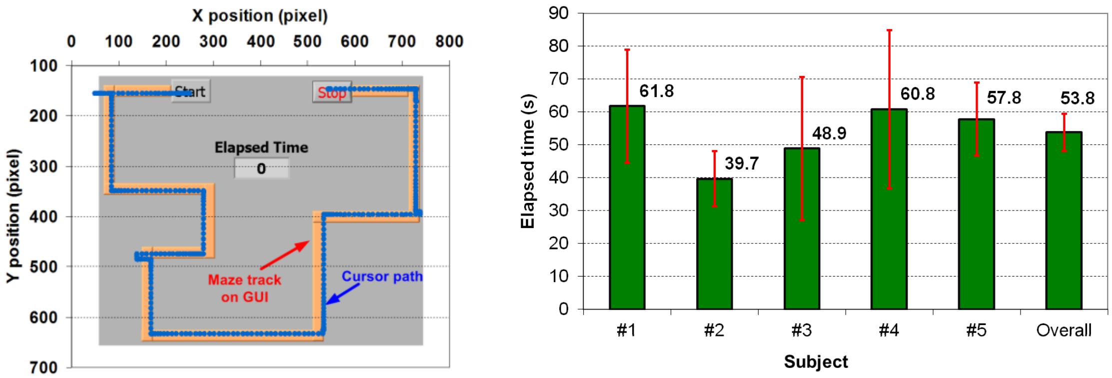
were required to repeat the experiment three times with three different control strategies: discrete, continuous, and gear-shift control. The discrete control strategy was tried with and without VF. Finally, the subjects were asked to navigate through the same track using the PWC's default proportional joystick. The navigation time, the number of collisions, and the number of issued commands (*NIC*) were recorded for each experiment. After completing the trial, each subject was asked to fill out a questionnaire including eight ratings questions to compare their perceptions of different control strategies.

5.3 Results

In following sections, the test results obtained from experienced subject A are separated from the other subjects to demonstrate the effect of experience in using the eTDS.

5.3.1 Computer Access Session

A) CA-1 Response Time Measurement: Figure 5.3a shows the accuracy vs. response time for five less-experienced subjects. It can be seen that an average performance for a TDS beginner with $PCC > 80\%$ can be achieved with $T \geq 0.6$ s. Fig. 16b shows the mean value and 95% confidence interval of the corresponding ITR for $T = 0.6 \sim 2$ s. The



(a) (b)

Figure 5.4: (a) Mouse cursor path recorded during the maze navigation experiment superimposed on the GUI track. (b) Mean values and 95% confidence interval of elapsed time for five naïve subjects to complete the maze navigation test along with the overall average.

highest *ITR*, which was achieved at *T* = 0.6 s, results from very short response time and moderate *PCC*. In practice, a good performance with *PCC* = 87% can be obtained with *T* ≥ 0.8 s, yielding an *ITR* of ~130 bits/min. Subject-A could, however, achieve a significantly better than average performance with *PCC* = 97.5% at *T* = 0.8 s, which is equivalent to an *ITR* = 178 bits/min.

B) CA-2 Maze Navigation: Figure 5.4a shows one of the mouse cursor trajectories recorded during the maze navigation experiment, superimposed on the maze track displayed on the GUI. Although the subject has missed the track at some of the corners, he has managed to bring the cursor back on track and complete the task. The average *ET* values together with their 95% confidence interval for different subjects and groups are shown in Figure 5.4b. The average *ET* of all 20 navigation experiments by five naïve subjects was 53.8 s, which was ~2.5 times longer than the time required for one of the subjects to navigate the mouse cursor through the maze using his hand. Considering the fact that the subjects had much more prior experience in moving the mouse cursor with their hand than with their tongue, this experiment showed the eTDS potential for

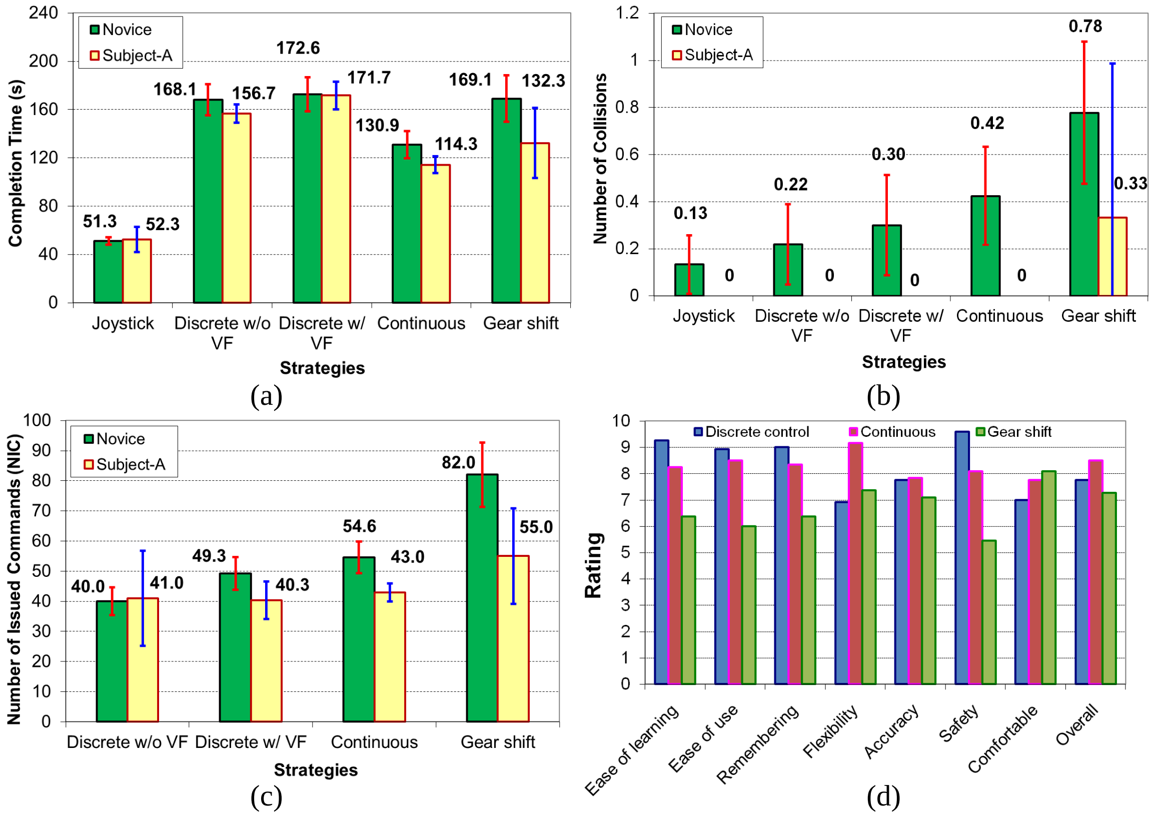


Figure 5.5: PWC navigation experimental results using the eTDS Gen-3 with different control strategies: (a) Average navigation time, (b) Number of collisions, (c) Number of issued commands (NIC), and (d) Subjective rating of three PWC control strategies based on a questionnaire filled by the subjects after the trials. The mean values along with their 95% confidence interval are shown for each variable.

performing complicated navigation tasks such as controlling a PWC in a crowded environment. Once again, subject-A performed much better than the average for less experienced subjects by achieving an *ET* = 38.3 s.

5.3.2 Powered Wheelchair Navigation Session

Figure 5.5 shows the average time, number of collisions, and *NIC* for both experiments of novice and subject-A in PWCN session. Overall, the continuous control resulted in the best performance with minimum elapsed time (130.9 s for novice subjects and 114.3 s for subject-A) and relatively low number of collisions (0.42 and 0 per trial for novice and subject-A, respectively). As expected, the discrete control was the slowest and safest with minimum number of collision. No essential difference in performance was observed in discrete control between novice subjects and subject-A, showing that this method barely relies on the users' prior experience. Gear-shift control was in between the other two mentioned strategies in terms of elapsed time, but it had the highest rate of collisions. Furthermore, subject-A performed obviously better than the other subjects with this strategy, showing that prior experience did matter in this case. The average time to complete the obstacle course using joystick was 51.3 s, which was 39% of the average time it took novice subjects using eTDS (45% for subject-A).

Figure 5.5c shows the average *NIC* for each strategy. It can be seen that subject-A has issued less commands than the other eleven novice subjects, especially in gear-shift control. That is perhaps due to issuing the control commands more accurately and more timely, which can lead to shorter navigation time.

Figure 5.5d shows the subjects' ratings of the three control strategies based on the questionnaire they filled in 8 categories. Continuous control received highest overall rating as well as the best flexibility and accuracy. This rating is in agreement with the quantitative experimental results shown in Figure 5.5a, and Figure 5.5b. The gear-shift control received the lowest overall rating due to its safety issue and difficulty in learning and remembering. Almost all subjects agreed that the discrete control was the easiest strategy to learn, use, and remember. It is also safer than the other strategies. However, its poor performance in terms of timing resulted in concluding that the continuous control is perhaps the best choice for driving PWC with tongue motion.

5.4 Discussion

The preliminary results from the able-bodied human trials have showed that the eTDS has the potential to substitute the arm and hand functions with tongue movements in both computer access and wheelchair control. The 0.8 s response time of the eTDS prototype with more than 87% accuracy is an acceptable performance for a device with 6 direct commands that are all simultaneously accessible to the user. Even though the hardware and SSP algorithm of these early eTDS prototypes still have significant room for improvement, the preliminary results are already better than the assistive technologies evaluated by Lau [77] as well as the recent tongue-computer interface (TCI) reported by Andreasen Struijk [78], which requires 1.9-2.9 s for each selection. The ITR achieved by the able-bodied subjects using eTDS prototype (138 bits/min) is about 5 times higher than the EEG based BCI devices (~26 bits/min) [61], which are all evaluated by lab-based experiments.

In wheelchair navigation, we observed that the subjects' performance in discrete control strategy is not significantly different with and without visual feedback. Similarly the subjects' prior experience does not seem to be very helpful in this case. These outcomes combined with the fact that subjects found this strategy to be safe, easy to learn, and remember, suggest that discrete control is probably the best strategy to begin with when one starts using the TDS.

We performed correlation analysis to study the relationship between navigation time and *NIC* for each control strategy. Results showed that they were positively correlated with the linear correlation coefficients greater than 0.8 in all cases. *NIC* depends on how accurately the subjects can remember the tongue gestures and repeat them consistently. When the subjects were not able to correctly issue the command that they had intended, they had to issue another command to correct the previous one, further increasing the

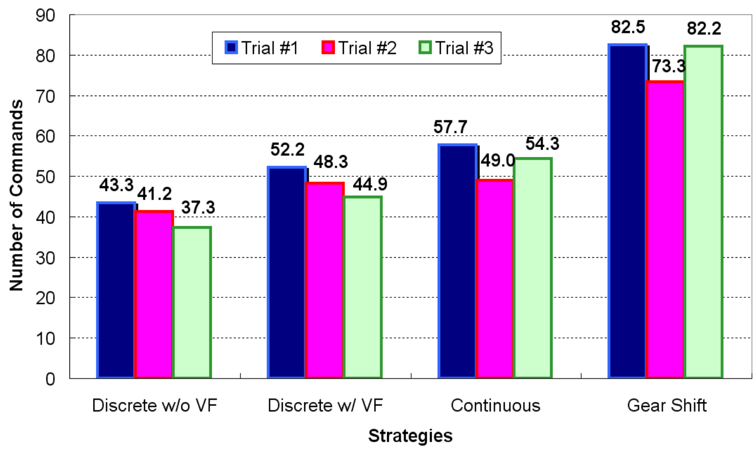


Figure 5.6: Average number of issued command (NIC) vs. the trial number for each control strategy. According to the one-way repeated measures ANOVA tests, there was no enough evidence to claim the learning effect during these early trials.

NIC and slowing the navigation. Another important parameter affecting *NIC* was the timing of the commands. For example, to perform a 90° left turn into an aisle, subject-A could drive the PWC to a proper position and issue a TL command at the right time to make a single sharp turn followed by an FD when the rotation was close to 90°. On the other hand, the novice subjects either started turning the PWC too early and too little or too late and too much, in which case they needed to issue a few other TL and TR commands to adjust the PWC position and enter the aisle. This is almost similar to what people do when learning how to drive a car.

Over time, the TDS user is expected to minimize the *NIC* and achieve better performance by remembering the tongue movements more easily (spatial accuracy) and executing them more timely (temporal accuracy). Figure 5.6 shows the relationship between average NIC and the trial number for each control strategy. One-way repeated measures analysis of variance (ANOVA) did not show enough evidence to claim the significant effect of the trial number on the *NIC* of all control strategies. More time and trials would be needed to observe the learning effect of using TDS for wheelchair control.

Robustness against the “Midas touch” problem is particularly important in wheeled mobility because an unintended movement of the PWC can lead to dangerous consequences. This is unfortunately a common problem in eye gaze systems and EEG-based BCIs [69]. In our trials, however, the eTDS was able to differentiate between the command related tongue movements and the tongue natural movements thanks to our stereo differential cancellation algorithm [86]. Most natural tongue movements, such as those related to speech, are in the sagittal plane, resulting in common mode variations in the magnetic field at the symmetrical locations of the sensor modules. Therefore, these components are cancelled in our differential transformations, and considered as the Neutral, which designates the tongue resting position [86]. To avoid the “Midas touch” problem during eating, when tongue movements are not only limited to the sagittal plane, the user is supposed to switch the eTDS to the standby mode, as explained in section 4.2.2.

Another expected observation from these human trials was that the subject’s performance in using the TDS was independent of his native language. In fact our human subjects were from five different native backgrounds, and we did not observe any relevance between their nationality and their performance. This is in contrast to the voice activated or speech recognition based ATs which are popular, especially among users who know English well. Therefore, we can expect the TDS to be used by people with severe disabilities regardless of their mother language.

5.5 Summary

Preliminary human trials on young able-bodied subjects demonstrated that the individuals with little or no prior experience with TDS can quickly and easily learn to operate the eTDS prototypes, and use these devices to substitute their hand and arm to access a computer and drive a powered wheelchair. A set of dedicated GUIs have been developed to measure the eTDS performance. The novice subjects achieved 138 bits/min information transfer rate when using eTDS to communicate with a computer. This is about 5 times higher than the EEG based BCI devices. Different TDS-PWC control strategies were tested in an obstacle course and compared with controlling the same PWC with its default proportional joystick. The continuous control strategy was found to be the most efficient method for driving a PWC with tongue motion. Using this method subjects with reasonable experience could complete the obstacle course using their tongue and eTDS prototype only ~2 times longer than using their fingers and a joystick.

CHAPTER VI

CLINICAL HUMAN TRIALS

This chapter presents the experimental design and results of the preliminary eTDS clinical human trials, in which the performance of the eTDS prototype was evaluated by 13 naive subjects with high level spinal cord injuries (C2~C5) at the Shepherd Center in Atlanta, GA. The experiment was divided into two sessions including computer access (CA) and powered wheelchair navigation (PWCN) session, with one week gap in between. The eTDS prototype used in these trials was eTDS Gen-4 (Figure 4.1d), which was built on a wireless headphone and interfaced to a laptop PC and a PWC.

6.1 Subjects

Thirteen human subjects (four females and nine males) aged 18 to 64 years old with high level SCI (C2~C5) were recruited from the Shepherd Center (Atlanta, GA) inpatient (eleven) and outpatient (two) populations. Among these subjects, eight were injured within six months before the trial and five had been injured for at least one year. Ten subjects were regular computer users prior to their injuries. Among the other three subjects, two had very limited knowledge of computers and one was completely new to PCs. Prior to this study, none of the subjects had been exposed to the TDS or participated in a similar research trial. Informed consent was obtained from all subjects. All trials were carried out in the SCI unit of the Shepherd Center with approvals from the Georgia Institute of Technology and the Shepherd Center institutional review boards (IRB).

Figure 6.1: A subject with SCI at level C4, wearing the eTDS headset and sitting in his own wheelchair with a 22” LCD monitor placed ~1.5 m in front of him during the computer access session.

6.2 Experimental Procedure

Each subject participated in two sessions: first, computer access and then, PWC navigation. The interval between the two sessions, depending on the subjects’ schedules, was almost one week. Each session ran for about three hours, and included TDS calibration, magnetic tracer attachment, pre-training, training, practicing, and testing steps. Regular weight shift schedule was strictly followed throughout every trial.

6.2.1 Computer Access Session

In the computer access (CA) session, subjects were either sitting in their own wheelchair or lying on bed with a 22” LCD monitor placed ~1.5 m in front of them, as shown in Figure 6.1. The eTDS headset Gen-4 was placed on the subjects’ heads and magnetic sensor positions were adjusted near their cheeks by bending the goosenecks. After sensor positions were fixed, subjects were required to go through sensor calibration and magnet attachment steps similar to those explained in section 5.2.1. Unlike the able-bodied

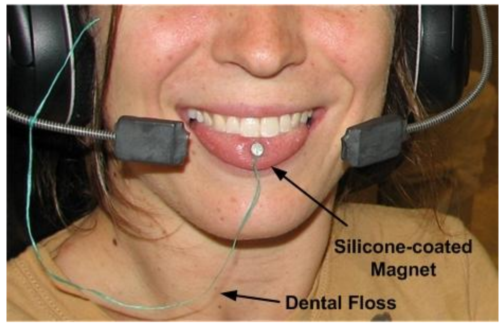


Figure 6.2: Magnet attachment for the clinical trials: a thin string of dental floss is attached to the magnetic tracer using super glue. The other end of the string is tied to the eTDS headset to eliminate any risk of swallowing or aspirating the magnetic tracer even if it is detached from the subjects' tongues. The magnetic tracer is also covered with silicone rubber to have a soft upper surface.

subjects, the patients with high level SCIs are very vulnerable, and therefore special care must be taken throughout the experiments to ensure the subjects' safety and comfort. For example, the magnetic tracer was sterilized and attached to a 20 cm string of dental floss using superglue. The top surface of the magnet was softened with a layer of medical grade silicone rubber (Nusil Technology, Carpinteria, CA) to prevent possible harm to the subjects' teeth or gums. The other end of the string was tied to the eTDS headset during the trials to avoid the tracer from being accidentally swallowed or aspired if it was detached from the subjects' tongues (Figure 6.2).

Tasks in the CA session were arranged from easy to difficult to facilitate learning as the trial went on. The number of eTDS commands was increased from 2 to 4 and then to 6 in three stages. At the beginning of each stage, subjects went through a pre-training step to identify their desired tongue positions for each command, similar to that explained in section 5.2.2. After proper tongue positions were indicated, subjects were asked to train the TDS by repeatedly placing their tongues in those positions for 10 times in a sequence. A new feature was added in training session to allow operators to supervise subjects' training by identifying and removing the outcast training points manually using an interactive GUI explained in section 4.6.1. [90].

A) CA-1 Playing a Computer Game with 2 Commands: The purpose of this test was to familiarize the subjects with TDS commands and train them on moving an object on a PC screen in one axis (either horizontal or vertical) using their tongues. In this test, the subjects were first asked to define two commands, Left and Right, and use them to play a "breakout" game by moving a paddle horizontally with their tongues to prevent a bouncing ball from hitting the bottom of the screen. Subjects were then instructed to define another two commands, Up and Down, and use them to play a "scuba diving" game by moving a scuba diver vertically to catch treasures while avoiding incoming fish and rocks. Subjects repeated each game 3 times and their scores were registered.

B) CA-2 Maze Navigation with 4 Commands: Subjects were asked to define and train the TDS with four commands: Left, Right, Up and Down. Then, subjects were instructed to complete a navigation task by using these four commands to move the mouse cursor through an on-screen maze as quickly and accurately as possible from the start to stop points, while the cursor path and elapsed time were being recorded [87]. The maze was wider at the beginning so that the subjects can start easily, and then gradually became narrower towards the end of the track. Subjects were required to complete four trials, one for practice followed by three for testing.

C) CA-3 Response Time Measurements with 6 Commands: Subjects were asked to add two more commands to the directional commands in B) for left and double mouse clicks. Then they were instructed to perform a set of response time measurement experiments similar to that explained in 5.2.4A. The only difference was that the mean

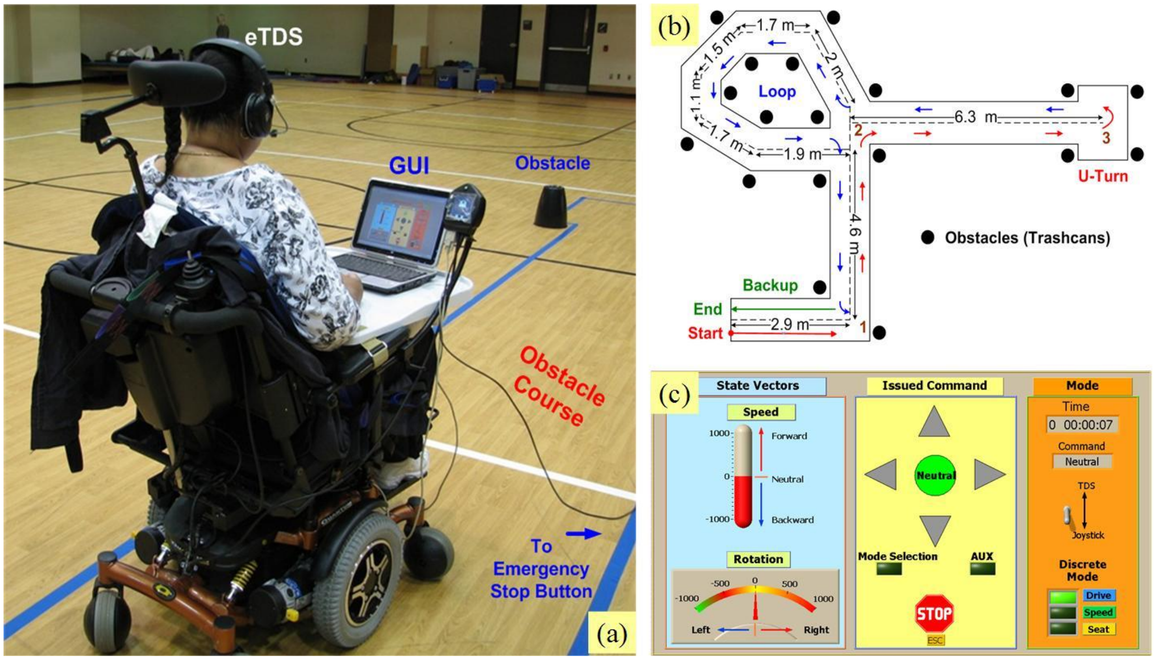


Figure 6.3: (a) A subject with SCI at level C4, wearing the eTDS prototype and navigating a powered wheelchair through an obstacle course. (b) Plan of the powered wheelchair navigation track in the obstacle course showing dimensions, location of obstacles, and approximate powered wheelchair trajectory. (c) The GUI provides users with visual feedback on the commands that have been selected.

probability of correct choices (*PCC*) was measured for T = 2, 1.5, 1.2, and 1 s, but not for T < 1 s. The response time T and the corresponding *PCC* were then used to calculate the *ITR*.

6.2.2 Powered Wheelchair Navigation Session

In powered wheelchair navigation (PWCN) session, subjects were transferred to a Q6000 powered wheelchair and went through the same preparation steps as in the CA session with a 12” laptop that was placed on a wheelchair tray in front of them, as shown in Figure 6.3a. They were asked to define four commands (FD, BD, TR, TL) to control the wheelchair state vectors in addition to the tongue resting position (N) for stopping, and practiced them on the maze navigation GUI, similar to CA-2, for about 5 minutes. Then they were required to navigate the wheelchair, using TDS, through an obstacle course, as fast as possible, while avoiding obstacles or running off the track. Three slightly different courses were utilized. However, they were all close to the layout shown in Figure 6.3b. The average track length was 38.9 $\pm$3.9 m with 10.9 $\pm$1.0 turns.

During the experiment, the laptop lid was initially opened to provide the subjects with visual feedback (shown in Figure 6.3c). However, later it was closed to help them see the track more easily. Subjects were required to repeat each experiment at least twice for discrete and continuous control strategies, with and without visual feedback. The gear-shift control strategy was excluded from this trial due to the safety concern. The navigation time, number of collisions, and number of issued commands were recorded for each trial.

To minimize the risk, the maximum speed of the wheelchair was limited to 0.9 mph. The operator had access to an emergency stop (ES) button on the wheelchair. During the experiment, the operator walked along with the subjects and was ready to hit the ES button if the subjects lost their control over the wheelchair movements.

6.3 Results

6.3.1 Computer Access Session

Nine out of 13 subjects said that they had not played any computer games prior to the trials. However, all of them were able to learn TDS quickly and use it to play games. In the CA-2, all subjects successfully completed at least three maze navigation trials. The performance of each subject was calculated as the average completion time of the last three trials. Figure 6.4 shows the completion time for each trial along with the overall performance, averaged across all 13 subjects. The average completion time was 65.9 s with a standard deviation of 26.6 s. A gradual decrement in the completion time was observed among three consecutive

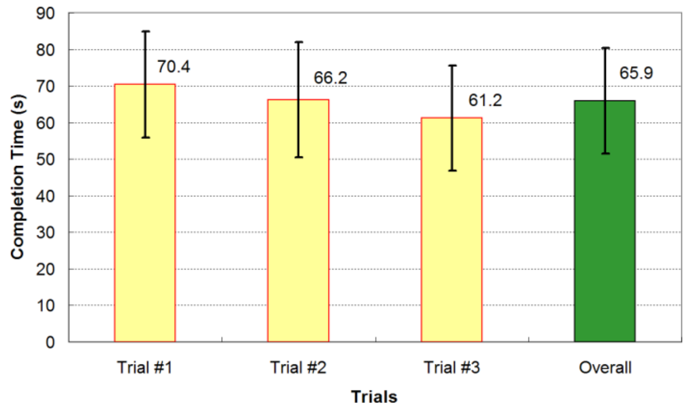


Figure 6.4: Average completion time along with 95% confidence interval across 13 subjects for three trials in maze navigation session.

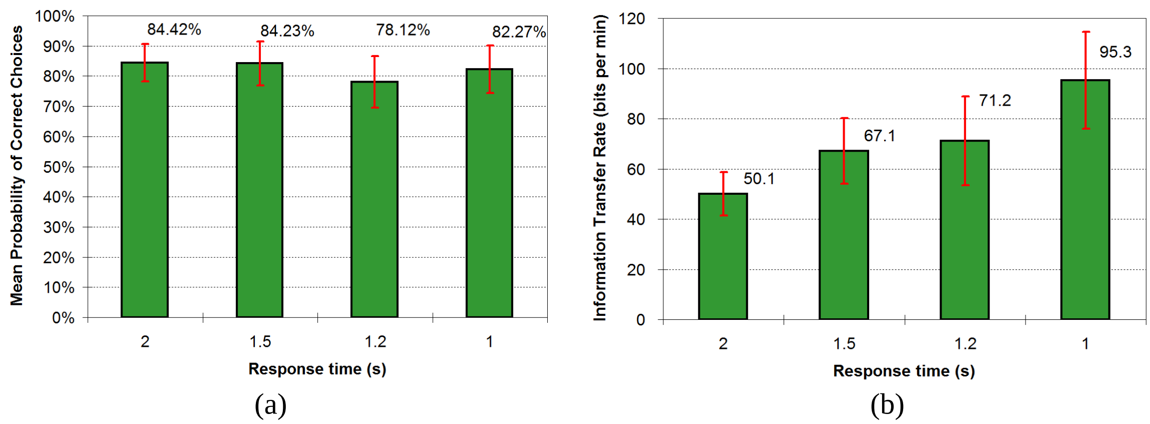


Figure 6.5: Response time measurement results: (a) Mean probability of correct choices vs. response time, and (b) Information transfer rate vs. response time.

trials, which can be an indication of the learning effect.

For each time limit, *T*, in CA-3, at least 40 commands were issued to calculate *PCC*. Data points for one of the subjects at 1.2 s and two subjects at 1 s were not recorded because of the early termination of their CA sessions due to their poor health. *PCC* and its 95% confidence intervals were calculated for all the available data for each *T* and the results can be seen in Figure 6.5a. The *ITR*, calculated for each *T*, are shown in Figure 6.5b. On average, a reasonable *PCC* of 82% was achieved with *T* = 1 s, yielding an *ITR* = 95 bits/min, which is about two times faster than the EEG-based BCI systems that are tested on humans [61].

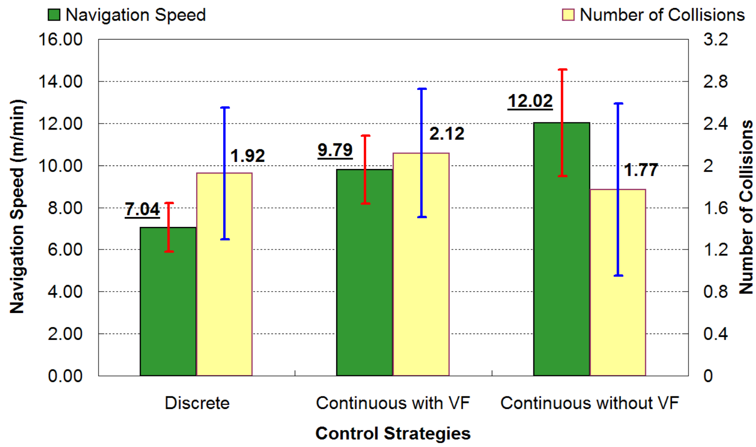


Figure 6.6: Average navigation speed and number of collisions for discrete and continuous control strategies, with and without visual feedback (VF).

6.3.2 Powered Wheelchair Navigation Session

All subjects successfully completed the powered wheelchair navigation tasks at least once. Each subject repeated the discrete control strategy for at least two trials. Continuous control strategy was also repeated at least twice with and without visual feedback for the majority of subjects. Four subjects tested the continuous control without visual feedback only once, and two subjects completed the trial for continuous control with visual feedback only once due to the early termination of their experiments for reasons unrelated to the TDS. Subjects' performance was measured by averaging the navigation speed and number of collisions across the last two trials in each category. If only one trial was completed, the result of that trial was directly used as the performance measure in completing that task. Figure 6.6 shows the average navigation speed and number of collisions along with their 95% confidence intervals during each experiment. In general, the continuous control strategy was much more efficient than the discrete control. Subjects consistently performed better without visual feedback by navigating faster with fewer collisions. These results demonstrate that subjects could easily remember and correctly issue the TDS tongue commands without requiring a computer screen in front of them, which may distract their attention or block their sight. Improved performance without visual feedback can also be attributed to the learning effect because it always followed the trials with visual feedback.

6.4 Discussion

This study demonstrated that the TDS can be easily used for both computer access and powered wheelchair control by naive subjects with high level SCI, who were quite diverse in terms of age, post injury period, prior experience with assistive technologies, and familiarity with computers. We have not yet conducted a direct side-by-side comparison between the TDS and other technologies such as BCIs, sip-and-puff, head pointers, eye trackers, and voice controllers. However, the TDS is unique in terms of providing multiple control functions over both computers and wheelchairs with a single device, thereby reducing the burden of learning how to use several assistive devices and switching between them, which often requires receiving assistance.

Table 6.1 compares the response time, number of commands, and calculated *ITR* of a few Tongue Computer Interfaces (TCIs) and BCIs that are reported in the literature. It can be seen that the TDS offers a better ITR compared to other switch based BCIs and TCIs due to its rapid response time. Recently, head controlled devices have been reported with higher bit rates [116]. However, it should be noted that these are considered pointing devices, similar to the computer mouse, which bit rates are derived based on a different model, known as the Fitts' law [117], as opposed to the TDS and other devices in Table I, which are discrete devices, and modeled by Wolpaw's ITR definition [61]. A limitation of the head controllers, however, is that they do not benefit users with no head motion and

Table 6.1: Comparison between the Tongue Drive System and other BCIs/TCIs*

Reference	Type	Number of commands	Response Time (s)	Information Transfer Rate ITR (bits/min)
Wolpaw [61]	EEG-BCI	2 - 4	3 - 4	25
Lau et al. [77]	TTK-TCI*	9	3.5	40
Andreasen [78]	TCI*	5	2.4	58
TDS (able-bodied subjects / SCI patients)	TCI*	6/6	0.8/1.0	133/95

*TCI: Tongue Computer Interface

rely on additional switches or dwelling time for mouse clicks, which may affect their usability.

In the PWCN session, we observed the real time and full control of the subjects over wheelchair movements through five simultaneously accessible tongue commands for cardinal directions and stopping. There was no noticeable delay in the wheelchair response to the subjects' tongue commands. On the other hand, in the EEG-based BCIs it takes about 2 s on average to issue a control command, which is not practical for stopping a wheelchair in an emergency situation [61]. Based on the results in Figure 6.6 and subjects' feedback, the continuous control strategy was preferred over the discrete strategy. Subjects also issued less commands when using the continuous method. Adding a latched mode, in which the users do not need to hold their tongues at a certain position to continue issuing a commonly used command, such as forward, was also suggested by several subjects, who already had this option in their sip-and-puff controllers.

In order to assess the effects of different factors, such as age, gender, and duration of injury on the computer access and wheelchair navigation performance, the subjects were categorized based on each of these factors and compared their performance accordingly (see Table 6.2). Since the number of subjects in each category was too small to conduct a

Table 6.2: Categorization of Subject for Performance Comparisons

Factor	Gender		Age (years)		Duration of Injury (months)	
	Female	Male	> 50	≤ 50	≤ 6	> 6
Number of subjects	4	9	5	8	8	5

statistical analysis, the discussion below is mainly based on the comparison of magnitudes of each performance parameter. For comparing computer access and wheelchair navigation performances, *ITR* from CA-3 and navigation speed and number of collisions from PWCN sessions were used respectively.

Effect of Age: It can be seen in Figure 6.7a and Figure 6.7b that there is a substantial difference between the performance of younger (≤ 50) and older (> 50) subjects. Younger subjects achieved higher *ITR* in all *T* values in CA-3 session. Younger subjects also tended to navigate the wheelchair faster, albeit with more collisions. It was probably because younger subjects had shorter reaction time and also faster learning ability compared to older subjects. However, it should also be noted that the performance gap was decreasing as subjects progressed through experiments. This suggests that the experience gained over a longer period of time can equalize users' performance regardless of being fast and slow learners.

Effect of Duration of Injury: Differences were found between subjects with relatively short (≤ 6 months) or long (> 6 months) post injury duration (Figure 6.7c and Figure 6.7d). The former group outperformed the latter in both CA and PWCN with performances in the range of 17% – 100% for *ITR* and 17% – 36% for wheelchair navigation speed. The hypothesis is that more recently injured subjects, who were beginning to learn and use assistive technologies, were probably more motivated in trying new devices. Hence, they could more easily accept and learn how to use the TDS with

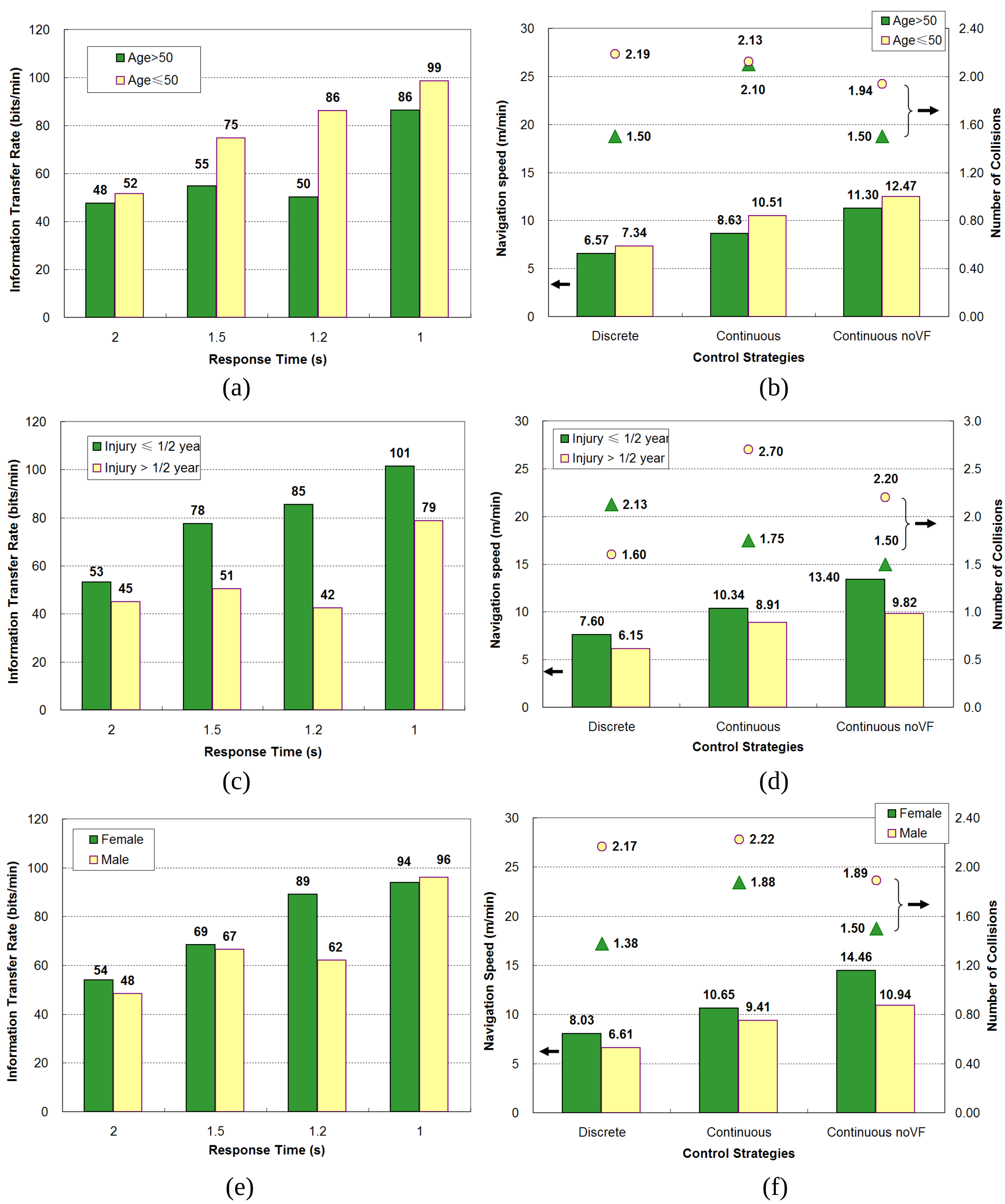


Figure 6.7: Comparing the effects of different factors on the subjects' performance in computer access and powered wheelchair control tasks through the ITR from the response time measurement session, and wheelchair navigation speed and number of collision from the PWCN session by: (a, b) younger (Age ≤ 50) vs. older (Age > 50) subjects, (c, d) subjects with shorter (≤ 6 months) vs. longer (> 6 months) post injury duration, and (e, f) female vs. male subjects.

less preference or bias. On the other hand, the group with older injuries had already quite used to their assistive devices (mostly sip-and-puff), and probably were not as motivated or open to learning and using a new device.

Effect of Gender: Female subjects performed with consistently comparable or higher ITR and wheelchair navigation speed, and fewer collisions than their male counterparts. The author could not find any particular reason for this difference other than considering the fact that the number of subjects in the female group was less than half of the male group. Therefore, this particular group might have been just a better fit for using the TDS. Additional tests in larger populations are needed for deriving a more accurate conclusion.

To minimize potential interference with the subjects' daily routines, almost all sessions were scheduled in the late afternoon or in the evening when subjects were generally tired after a full day of therapeutic exercises and rehabilitative activities at the Shepherd Center. As a result, some of the subjects, particularly the elders, seemed to be tired at the beginning of the 3-hour sessions and exhausted at the end, to the extent that we had to cut the number of repeated trials to complete some of the sessions earlier. This situation may have degraded the subjects' overall performance and should be avoided in future evaluations. The most realistic condition would probably be a randomized testing schedule that is evenly distributed throughout the day.

The eTDS prototype used in these trials has significant room for further improvements in its hardware, SSP algorithm, and GUI software. Several subjects reported reduced sensitivity and responsiveness of the TDS to their tongue commands after the headset position was inadvertently changed in a regular weight shift. In such cases the sensor calibration and TDS training steps had to be repeated. A similar issue can arise when someone accidentally changes the sensor positions by moving the goosenecks. This is a concern that is resulted from the use of off-the-shelf components for building the eTDS prototype as opposed to a customized headset design for this particular application.

6.5 Summary

In summary, the first clinical trial on thirteen subjects with high level SCI demonstrated that the eTDS prototype can potentially provide its end users with effective control over both computers and wheelchairs. eTDS in its early form, tested by naive SCI subjects, is twice as fast as EEG-based BCIs that are tested on trained humans [61]. Subjects' ability to perform all the tasks indicated that the eTDS can be easily and quickly learned with little training, thinking, or concentration. The learning effect, on the other hand, showed that it is very likely that the users' performance could improve over time if they use eTDS on a daily basis. According to the results, eTDS performance can also be affected by the users' age, gender, and post injury duration. Additional experiments are needed to observe the end users' performance over long periods of time.

CHAPTER VII

ASSESSMENT OF TONGUE DRIVE SYSTEM IN MEDIUM TERM USAGE

The main purpose of this work is to assess the learning process of the Tongue Drive System (TDS) in medium term usage for both computer access and wheelchair control, as well as explore the limiting factors in the current TDS prototype. The results can lead the way in improving the usability of the TDS and similar tongue operated assistive technologies.

In our earlier studies, we have evaluated the performance of TDS for both computer access and wheelchair control in single-session trials by able-bodied subjects, as well as patients with high level spinal cord injury (SCI) with a magnet temporarily attached using tissue adhesive. However, these trials last only for a few hours, and do not sufficiently demonstrate the learning process, costs, or benefits of using the TDS on a long-term basis. Unlike short-term experiments in which the magnetic tracer could be attached to the subjects' tongues using a tissue adhesive, medium and long term use of the TDS requires semi-permanent attachment of the magnetic tracer to the subjects' tongues. This can be done by piercing the tongue and inserting a tongue stud with the magnetic tracer inside it. To verify the idea of using a tongue piercing to fix the magnet, we have recruited able-bodied subjects, who already have tongue piercing, and had them wear the specially designed magnetic tongue studs (more details later in section 7.1) throughout the study. These subjects were asked to participate in a set of experiments to test TDS performance over five sessions during five weeks in order to observe the learning process, which is a key factor in the acceptability and adoption of a new assistive technology (AT).

Each session consisted of three hours of computer access (CA) and one hour of powered wheelchair navigation (PWCN). In CA, a set of new experiments was designed, based on ISO9241-9 standard [118], to evaluate the TDS performance of controlling a mouse cursor by completing pointing and selecting tasks. These tasks include: one-direction tapping in horizontal and vertical directions, center-out 2-D tapping, and multi-direction tapping. In addition, tasks similar to those performed in one-session trials, such as on-screen 2-D maze navigation and response time measurements, were also included. Each trial also included PWC drive by TDS through an obstacle course after the CA part of each session.

In this chapter we have only included the results of maze navigation, response time measurement, and powered wheelchair control. Readers can refer to our previous publications [120], [121] for more details on the rapid tapping tasks of computer access.

7.1 Magnetic Tongue Stud

Barbell shaped magnetic tongue studs with different post gauges and lengths, designed and fabricated by Anatometal (Santa Cruz, CA), are used to explore the feasibility of tongue piercings to the fix magnet on the tongue during medium term assessment. The M&M shaped ball (Ø8 mm $\times$ 3.5 mm) shown in Figure 7.1, which is laser-welded to the post, contains a disk-shaped (Ø4.8 mm $\times$ 1.5 mm) rare earth permanent magnet (K&J Magnetics, Jamison, PA). The magnetic flux density on the upper surface of the M&M ball is 1194 $\pm$83 Gauss on average. The lower ball is tightly screwed on to the post with a large number of threads. The subjects, who already have tongue piercing, were required to wear these specially designed magnetic tongue studs throughout the performance

Figure 7.1: A custom designed magnetic tongue stud with a permanent magnet embedded in its upper ball. It was worn by the subjects throughout the medium term study.

assessment, instead of having the magnet temporarily glued on to their tongue using tissue adhesive.

7.2 Subjects

Nine healthy able-bodied subjects, four male and five female, with an age range of 19 – 28 years old, were recruited from the Georgia Institute of Technology and Georgia State University student population. All of the subjects had their tongue piercing in the middle line, between tip and frenulum, for more than three months. All of them are regular computer users and had no previous experience with TDS. Except for one subject, all the subjects were right handed. The necessary approval was obtained from Georgia Tech's institutional review board. Informed consent was collected from all subjects during the first session before the experiment started.

7.3 Experimental Procedure

The subjects were scheduled for one experiment session per week and needed to complete five sessions over five weeks. Average CA and PWCN durations were 5 and 1.5 hours, respectively, for the first session and 2.5 and 1 hour, respectively, for the remaining sessions. During their first visit, subjects were provided with a sterilized

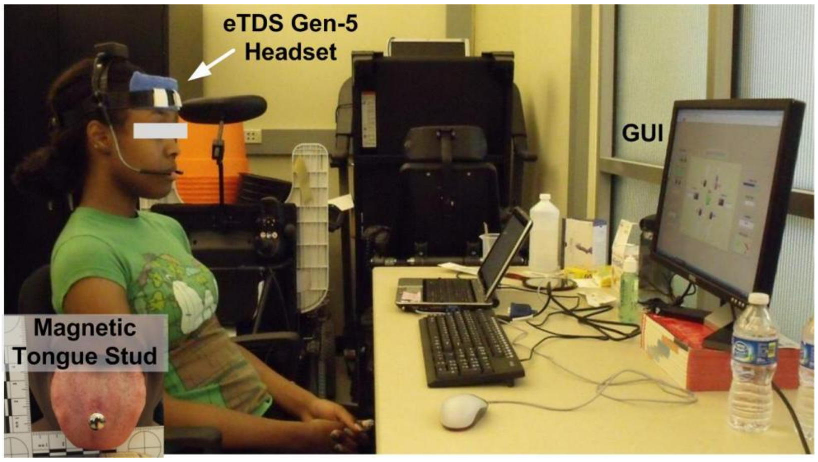
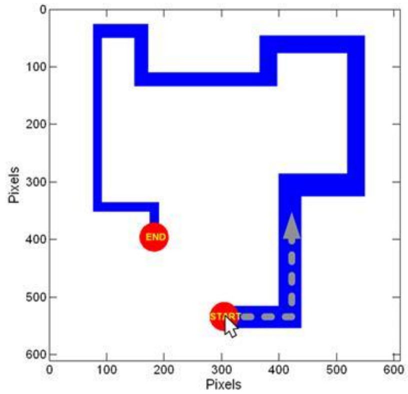


Figure 7.2: The computer access experimental setup in medium term TDS performance assessment. One of the subjects sat 1 m away from a 22” LCD monitor, performing the response time measurement task.

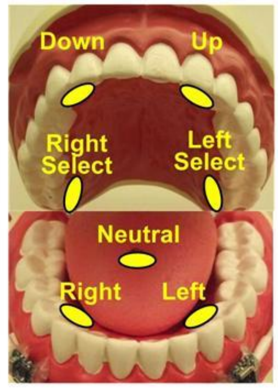
magnetic tongue stud. They were asked to substitute their own stud with this magnetic tongue stud and wear that throughout the duration of the study. In each session, the subjects were asked to wear the eTDS headset, go through TDS calibration, pre-training, training procedures similar to that mentioned in section 5.2, and then complete a set of tasks related to the computer access and wheelchair control.

7.3.1 Computer Access

The CA experiments were conducted in the GT-Bionics lab at the Georgia Institute of Technology. During the experiment, the GUI, developed in the LabVIEW environment, was presented to the subjects sitting 1 m away from a 22” LCD monitor with 1280 × 800 pixel resolution, shown in Figure 7.2. Subjects performed six tasks (with the number of employed TDS commands in parentheses): horizontal (2) and vertical (2) unidirectional tapping, on-screen maze navigation (4), center-out tapping (4), response time measurement (6), and multidirectional tapping (6). Here we only report on the maze navigation (4) and response time measurement (6) tasks, similarly to those performed in



(a)



(b)

(c)

Figure 7.3: (a) Task screen for maze navigation. (b) Recommended tongue positions for six TDS tongue commands plus the tongue resting position, which is considered as a neutral command. (c) Designated keys on the keypad to resemble the TDS commands' positions.

single-session trials. To facilitate learning particularly in the first session, these tasks were arranged from easy to difficult in terms of the required number of TDS commands.

A) CA-1 Maze Navigation: In the maze navigation task, subjects were instructed to move the mouse cursor through a customized on-screen maze from the START circle to the END circle as fast as possible and try to stay within the blue track as much as possible. At the beginning of each trial, the mouse cursor was automatically positioned in the center of the START cycle and subjects were instructed to move the cursor after they saw the red START circle turned green. The experiment automatically terminated when the subjects moved the cursor within the END circle. The maze had twelve sections and each three sections had the same width (38, 30, 23, 15 pixels) but various lengths. The maze started with a wider section at beginning so that the subjects could start easily, and became narrower towards the end. An example maze design is shown in Figure 7.3a.

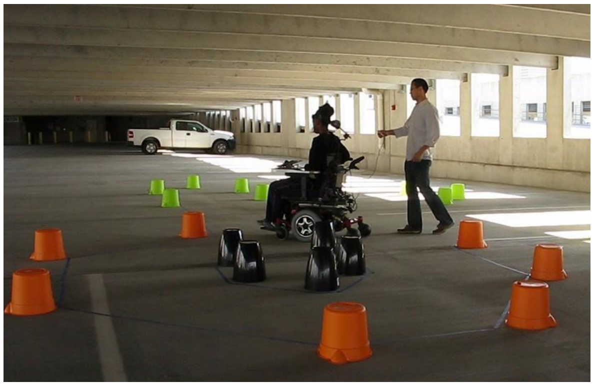
The subjects were required to complete the task using both TDS and a standard keypad in a randomized order. In TDS, four directional commands (LEFT, RIGHT, UP and DOWN), with positions indicated in Figure 7.3b, were used to move the mouse cursor in four directions. When using the keypad, the subjects were required to press a subset of adjacent keys on a standard keypad which spatially mapped to TDS's four direction commands, as shown in Figure 7.3c, using their right index fingers. The cursor movement in each direction was in an unlatched mode, meaning that subjects should keep issuing a direction command to maintain the cursor movement in that direction. As the cursor moved in a certain direction, its speed increased linearly at the rate of 500 pixels/sec^2 until it reached a maximum level of 350 pixels/sec. The rate of acceleration and maximum speed were chosen experimentally based on the pilot experiments in the developmental phase.

The task was repeated four times for each device, the first for practice and the remaining three for performance measurement. To minimize the memory effect, four out of five different maze designs were randomly selected for the four rounds.

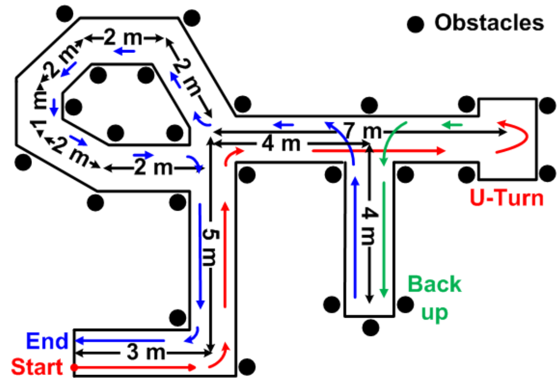
B) CA-2 Response Time Measurement: The subjects were instructed to perform a set of response time measurement experiments similar to that explained in 5.2.4A. The mean probability of correct choices (PCC) was measured for T = 2, 1.5, and 1 s, each of which was repeated for four rounds, and each round contained 20 randomly selected commands. The first round was regarded as practice and the results from last three rounds were used to calculate the performance measures. This task was performed with TDS only.

7.3.2 Powered Wheelchair Navigation

The PWCN part of each session was performed in a spacious indoor garage environment (see Figure 7.4a) to give the subject enough space to move the chair around and minimize the danger of accidentally hitting any pedestrians, walls or other unwanted objects. The PWCN was always conducted after computer access (CA) because it required more



(a)



(b)

Figure 7.4: (a) Experimental setup for the wheelchair drive part of the medium term TDS performance assessment. (b) Plan of the obstacle course showing its dimensions, obstacles locations, and approximate driving trajectory.

experiences of using TDS, which could be gained by the subjects through several CA tasks. PWC tasks in this study consisted of driving through a modified obstacle course that was roughly 50 meter long and had 13 turns and 24 obstacles (Figure 7.4b). Subjects were asked to navigate the PWC as fast as possible and try to avoid hitting any obstacles or driving outside the track as much as possible. Driving through the obstacle course required using all the TDS commands and included making a U-turn, backing up, and fine tuning of direction in a limited space. During navigation, subjects were also instructed to make an immediate stop, as soon as they heard a randomly generated auditory cue which was played once per round while the PWC was moving at its maximum speed.

During the experiment, the subjects were required to navigate the wheelchair through the course using three different control strategies (unlatched, latched, and semi-proportional control as explained in section 4.5.2), each of which was repeated four times, one for practice followed by three testing rounds. The laptop was placed on the tray in front of the subjects, with its lid opened in the practice round to provide subjects with visual feedback about the issued commands and closed in the three testing rounds to

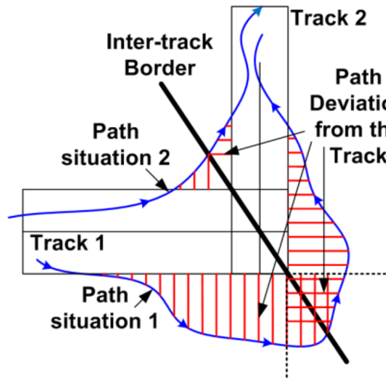


Figure 7.5: The path deviation of the maze navigation task is calculated based on the relative position of the cursor path to the inter-track border.

allow subjects to have a better view of the course. The operator held a mechanical stop button while walking along with the subjects, and was ready to stop the wheelchair if it was out of the subjects' control.

7.3.3 Performance Measures

For maze navigation, the performance measures include task completion time (*TCT*) and navigation error (*NE*). *TCT* indicates the speed of each device in navigating mouse cursor, and was calculated from the recorded time during the maze navigation. *NE* is the summation of all the deviations (*SoD*) of the path from the track edges divided by 1000 as a measurement of navigation accuracy. Figure 7.5 shows a typical portion of the maze and two general trajectories of cursors passing through track 1 and 2. The border of these two tracks is defined as inter-track border. The deviation is calculated as the perpendicular distance between the points on the cursor path and the outer boundary of track 1 or 2 depending on whether the cursor has passed over the border or not, respectively. Figure 7.5 also shows two cases in which the path is passing along interior and exterior sides of track corners. In the latter case, the deviations are calculated relative to the extensions of the track edges.

For the response time measurement task, we measured the mean probability of correct choices (*PCC*) for each response time *T*, and then calculated the information transfer rate (*ITR*) using equation 5.1 [61].

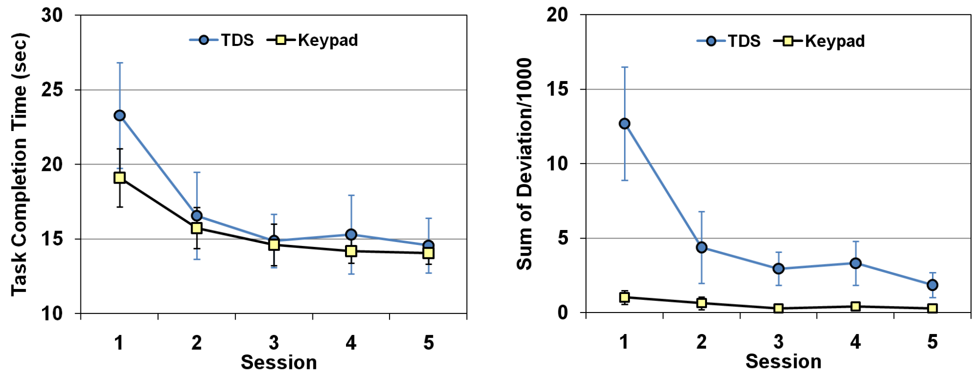
The performance measures for the wheelchair navigation task include the completion time (*CT*), the number of adverse event (*AE*) and the emergency stop duration (*ESD*). The *CT* indicated the navigation speed of each control strategy and was recorded by the operator during the experiment. The *AE* included the collisions with any obstacles and driving outside the track. The number of *AE* indicated how accurately the subjects could drive the wheelchair using different strategies and were counted by the operator during the experiment. *ESD* reflected how quickly the subject could stop the wheelchair in a dangerous condition. It was captured by the GUI from the start of the auditory cue till the complete stop of the PWC.

The reported performance measures were calculated by first averaging within each individual subject across three testing rounds and then averaging across all nine subjects. The 95% confidence intervals were also calculated to indicate the variations of each measure.

7.3.4 Results

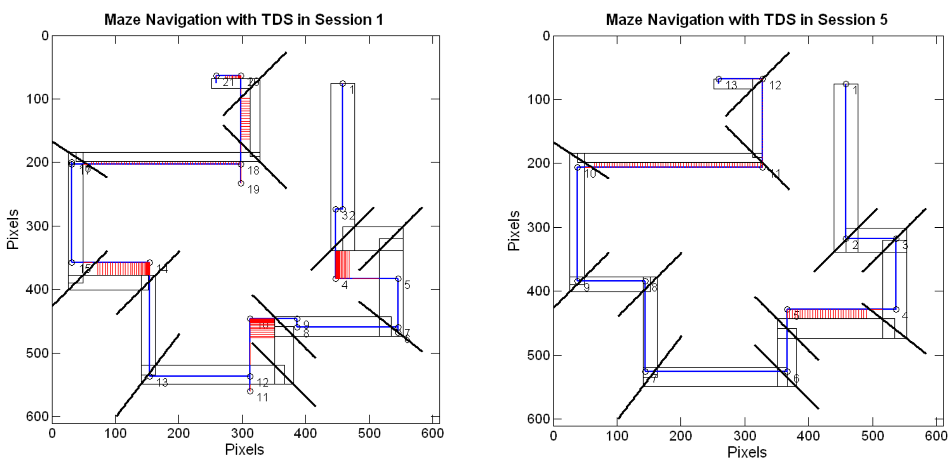
<u>A) Maze Navigation</u>

Figure 7.6 show the *TCT* and *SoD* of both TDS and keypad in completing the maze navigation task. One-way repeated measures (RM) analysis of variance (ANOVA) was conducted on both the TDS *TCT* and *SoD* with session as a factor showing significant effect of session on both TDS performance measures (both $p < 0.01$). Helmert contrasts showed that session effect on both TDS *TCT* and *SoD* was not significant from the 2nd



(a) (b)

Figure 7.6: (a) Task completion time. (b) Navigation error of maze navigation task.



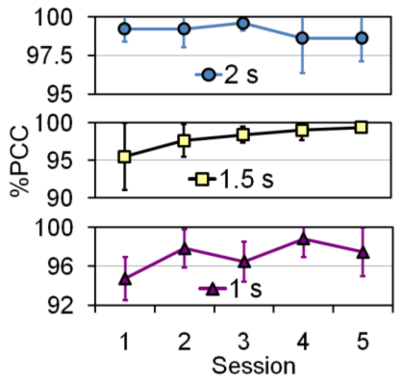
(a) (b)

Figure 7.7: The cursor path of one subject through a certain maze design in the (a) 1st session (*SoD* = 8.54, *TCT* = 18.8 sec), and (b) 5th session (*SoD* = 1.33, *TCT* = 13.3 sec)

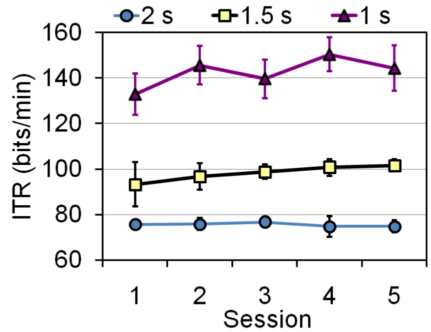
session (p = 0.115 and 0.174 respectively), suggesting that both *TCT* and *SoD* had reached a plateau.

Paired t-test was applied to compare the performance of TDS with that of keypad in the 5th session. The results show there is no significant difference between TDS and keypad *TCT*s in the 5th session (p = 0.43), while TDS 5th session *SoD* was significantly higher than that of the keypad which was 0.28 ±0.32 (p < 0.01).

Figure 7.7 shows typical cursor trajectories recorded for the same subject in the 1st and 5th sessions with TDS. It clearly shows an improvement of *SoD* (*SoD* = 8.54 and *TCT* =



(a)



(b)

Figure 7.8: (a) The mean probability of correct choices (PCC). (b) Information Transfer Rate (ITR) of TDS over five sessions.

18.8 sec for the 1st and *SoD* = 1.33 and *TCT* = 13.3 sec for the 5th session).

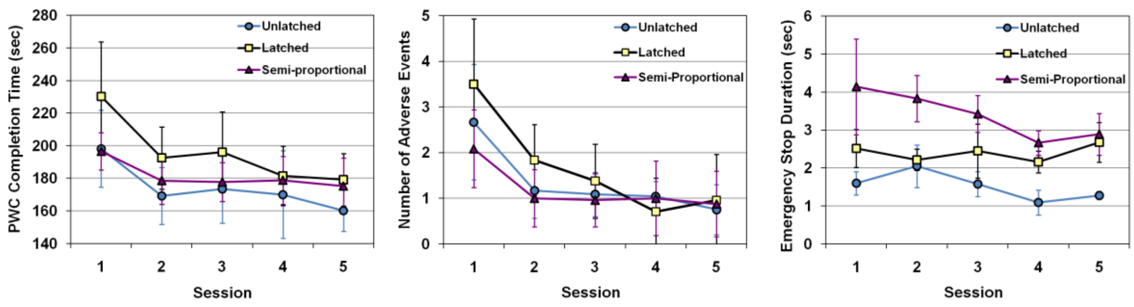
B) Response Time Measurement

The results of the response time measurements are shown in Figure 7.8, which includes the mean probability of correct choices (*PCC*) and the information transfer rate (*ITR*) for different *T*s. RM ANOVA revealed no significance in both *PCC* and *ITR* throughout the 5 sessions for any of the time intervals. At the end of the 5th session, a maximum 144 bits/min *ITR* was achieved with 97% *PCC* at 1 sec response time, showing a considerable improvement compared to our earlier studies.

C) Powered Wheelchair Navigation

One of the subjects performed extremely bad in wheelchair navigation, and was considered as an outlier and excluded from the analysis. Therefore, the following results are based on the performance of eight remaining subjects.

RM ANOVA was applied to all the PWCN performance measure considering both session and control strategy as factors. Regarding the Completion Time (*CT*), as shown in Figure 7.9a, both effects of strategy ($p < 0.05$) and session ($p < 0.01$) were significant. Helmert contrasts showed that session effect was not significant from the 2nd session (p =



(a) (b) (c)

Figure 7.9: Results of PWC navigation task: (a) Completion time, (b) Number of adverse events, including collisions and Out-of-Tracks, and (c) Emergency stop duration (sec).

0.474), suggesting that *CT* had reached a plateau. In the last (5^{th}) session, the subjects achieved 160.1 $\pm$18.2 sec, 179.1 $\pm$23.2 sec, and 175.3 $\pm$24.6 second of total completion time with unlatched, latched and semi-proportional strategies, respectively. Pair-wise comparison with Bonferroni adjustments applied to the last session result further shows that the CT of unlatched strategy was significantly different from that of the latched ($p < 0.05$), but not from the semi-proportional strategy. Also, latched and semi-proportional strategies were not significantly different (p=0.333) in term of *CT*.

Figure 7.9b shows the number of *AE* of all three control strategies measured over five sessions. RM ANOVA shows that the effects of strategy was not significant ($p = 0.334$) but the effect of session was significant ($p < 0.01$). Helmert contrasts showed that session effect was not significant from the 2^{nd} session ($p = 0.200$), suggesting that *AE* had reached a plateau. The subjects achieved 0.75 $\pm$0.66, 0.96 $\pm$1.44 sec, and 0.88 $\pm$1.04 *AE* in the 5^{th} session with unlatched, latched, and semi-proportional strategies, respectively.

As far as *ESD* (see Figure 7.9c) is concerned, both effects of strategy ($p < 0.01$) and session ($p < 0.05$) were significant. Helmert contrasts showed that session effect was significant throughout the five sessions. In other words, this performance measure had not reached a plateau after five sessions. We further applied one way ANOVA on the last session results of the *ESD*, followed by pair-wise comparison with Bonferroni adjustment. It shows that *ESD* in the unlatched strategy is significantly lower than those of latched and semi-proportional (both $p < 0.01$), while there is no significant difference between *ESD*s of latched and semi-proportional ($p = 1.000$).

7.3.5 Discussion

We have reported the result of computer access tasks of on-screen maze navigation and random command (rendering TDS *ITR*) as well as powered wheelchair drive with three strategies using TDS throughout five sessions in five weeks. The main purpose of this study was to explore the TDS learning process, including its initial performance, total achievement through five sessions, and the occurrence of any plateaus in the performance measures and their levels.

Maze navigation was performed with index finger keypad as well as TDS with the purpose of building a benchmark with which TDS can be compared. Statistical analysis shows that both *TCT* and *SoD* of TDS had significantly improved from the 1st to 5th session, which is evidence of learning effect. Although statistical methods showed no significant difference from the 2nd session for TDS *TCT* and *SoD*, suggesting early plateaus, in fact, as sessions went by the averages and variability dropped, hence performance improved. The effect of the device was not significant in *TCT*, but the *SoD* results revealed a superior performance of index finger keypad compared to TDS in term of the navigation accuracy. However, as it can be seen from Figure 7.6b, this performance difference is narrowing down with the progress of the session. Although we could not find any direct comparison in the literature between the movement speed and accuracy of the tongue versus index finger, we can relate this outcome to the subjects' benefiting from visual and more pronounced tactile feedbacks when selecting and pressing a button down and releasing it versus touching a specific tooth with their tongues and returning to the resting position. In addition, this performance difference may also be resulted from the level of familiarity with each device. All subjects were regular computer users and had been using keypad on daily basis for years, while they had only used TDS a few hours each week for five weeks. It is reasonable to expect the performance difference between keypad and TDS to become smaller or even statistically non-significant once subjects use the TDS on a daily basis over an extended period of time.

For response time measurement, statistical analysis did not show significant difference of *ITR* and *PCC* among five sessions. In other words, statistically speaking, no learning effect was observed in completing this specific task. The best *ITR* in the 1st session was 132.9 $\pm$ 13.9 bits/min with *PCC* of 94.7% at 1 sec time interval, while the maximum achieved ITR was 150.3 $\pm$ 11.5 bits/min with *PCC* of 98.8% at 1 sec time interval in the 4th session. Originally, we were expecting to observe the accuracy drop as the time interval decreased and to calculate the maximum *ITR* corresponding to an acceptable *PCC*. However, the subjects performed pretty well and achieved high *PCC* (> 94%) even at the shortest time interval (1 sec) in the 1st session, leaving little room for them to improve with the progress of the session. This implies that the experiments were not difficult enough to challenge the subjects to show a significant learning effect. Based on these observations, we can hypothesize that TDS *ITR* could be higher and the learning effect would be more profound if the time intervals become challengingly lower, such as 0.8 or 0.6 sec.

All the PWC performance measures improved from the first to the last session.

Unlatched strategy turned out to be the fastest strategy in the 5th session, while latched and semi-proportional strategies were not significantly different from each other in terms of the speed. This result can be partially related to the design of the obstacle course, which requires the subjects to turn and stop frequently. Unlatched control has the advantage of operating in such condition, benefiting from its quick response to the stop command, which is issued in this strategy by simply returning the tongue back to resting position. However, for daily wheelchair driving, latched and semi-proportional control may be more favored since they do not require continuously issuing direction commands, which could potentially result in tongue fatigue after long time usage. The average numbers of *AE* for all three strategies were not statistically different from each other and dropped below one in the 5th session. This means that subjects could accurately navigate the wheelchair with almost minimal error, e.g. driving out of track or hitting obstacles less than once per round, using any of these strategies. With unlatched strategy, the subjects could stop the wheelchair with an acceptable amount of delay (1.3 ± 0.2 seconds) to respond to an emergency stop request in 5th session. Latched and semi-proportional strategies unfortunately had an *ESD* higher than 2 seconds even in the 5th session, which by no means were acceptable for an immediate stop. Therefore, we suggest the TDS PWC users use a mechanical switch, such as a mini-cup switch mounted on the headrest, as an emergency stop button to stop the wheelchair immediately when needed.

7.4 Summary

We have quantitatively and comparatively evaluated the performance of the latest eTDS prototype Gen-5 in medium term usage for both computer access and wheelchair control by nine able-bodied subjects with the magnetic tracer attached to their tongue using a tongue piercing. These subjects, who already had tongue piercings, wore a specially designed magnetic tongue stud as opposed to their own regular stud, and performed the experiments in five sessions over five weeks. The results showed that nearly all the TDS performance measures have significantly improved from the first to the last session, and some of these plateaued over the course of the experiment, which is an indication of a learning effect. The comparison between subjects' performance with the TDS and keypad provided valuable insight into the human factors of the tongue motion and a few limiting factors of the current TDS, which can lead the way in improving future versions of the TDS.

CHAPTER VIII

MULTIMODAL TONGUE DRIVE SYSTEM

8.1 Background and Motivation

It has been understood that any interface that is designed around only one mode of input may not be fast and flexible enough to meet the diverse needs of the end users in today's hectic and demanding life conditions [122]. A multimodal device that expands the access beyond one input channel, on the other hand, can potentially improve the speed of access by increasing the information transfer bandwidth between users and computers [123], [124]. A clear example of this is the use of both mouse/touchpad and keyboard by the majority of able-bodied users either on their desktop or laptop machines. In addition, multimodal assistive technologies (ATs) increase the number of alternatives available to users to accomplish a certain task, thus give users the ability to switch among different input modalities, based on their convenience, familiarity, and environmental conditions [125]. Multimodal ATs can also provide their users with more options to cope with fatigue, which is an important factor that affects the acceptability of ATs, and therefore can result in greater user satisfaction and technology adoption.

The Tongue Drive System (TDS) in its current form has been mainly designed to substitute mouse cursor movements in cardinal directions plus clicking functions by offering users with six simultaneously accessible commands, which are associated with particular user-defined positions in the mouth, that are activated when they are reached by their tongues. Even though TDS can provide full typing capability when it is combined with an on-screen keyboard, its relatively small number of discrete commands, when compared to a full keyboard, and fast response time (< 0.5 s) makes it more suitable for mouse cursor control as opposed to typing [87].

On the other hand, speech recognition technology can offer an almost unlimited number of available commands, and has been regarded as one of the most efficient ways for text entry. Individuals with severe disabilities can benefit from this technology as long as their vocal abilities are intact. The speech recognition software also allows its user to control the mouse cursor movements using a set of predefined voice commands. However, the response time would be relatively long because a complete command such as “move mouse right” should be uttered in addition to short pauses before and after speaking each command. Moreover, the ambient acoustic noise can significantly degrade the quality of sound acquired by the microphone and affect the accuracy of the speech recognition tool. As a result, a system that relies on the speech input only might show poor performance in translating users’ verbal commands or becomes even completely irresponsive in noisy and outdoors environments.

The main objective of the work presented in this chapter is to combine TDS and speech recognition technology to develop a unified and highly integrated AT, called multimodal Tongue Drive System (mTDS), which can take advantage of the strength of each modality to provide people with severe disabilities with more efficacious, flexible, and reliable control over target devices, such as computers, cellphones or powered wheelchairs, in various personal and environmental conditions. We expect the mTDS to offer its end users with the best of both modalities in the following ways: 1) Increase in speed since each modality can be used for its optimal target tasks and functions; 2) Allowing users to select either technology depending on the personal and

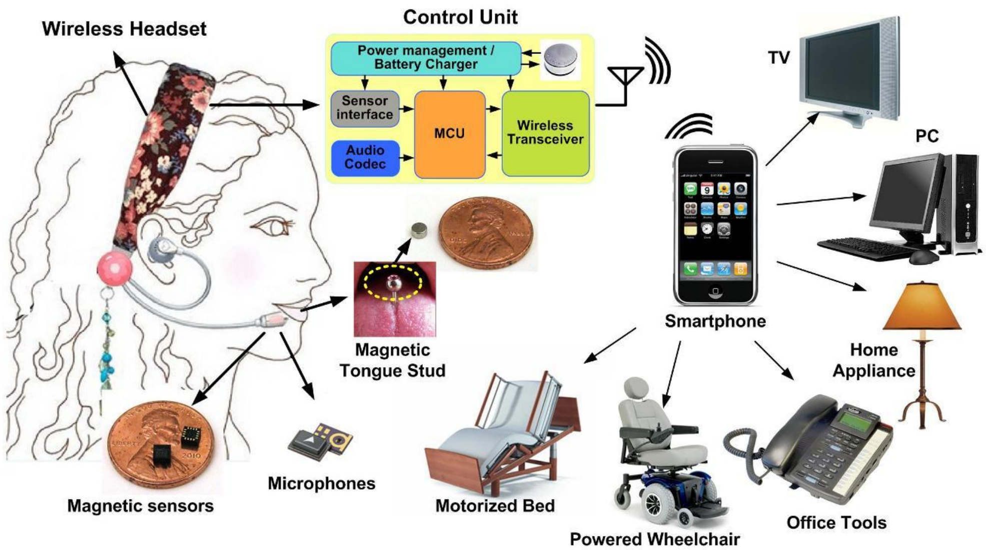


Figure 8.1: The top-level block diagram of multimodal Tongue Drive System (mTDS).

environmental conditions, such as weakness, fatigue, acoustic noise, and privacy [123]; 3) Provide users with a higher level of independence by eliminating the need for switching from one AT to another, which often requires receiving assistance from a caregiver.

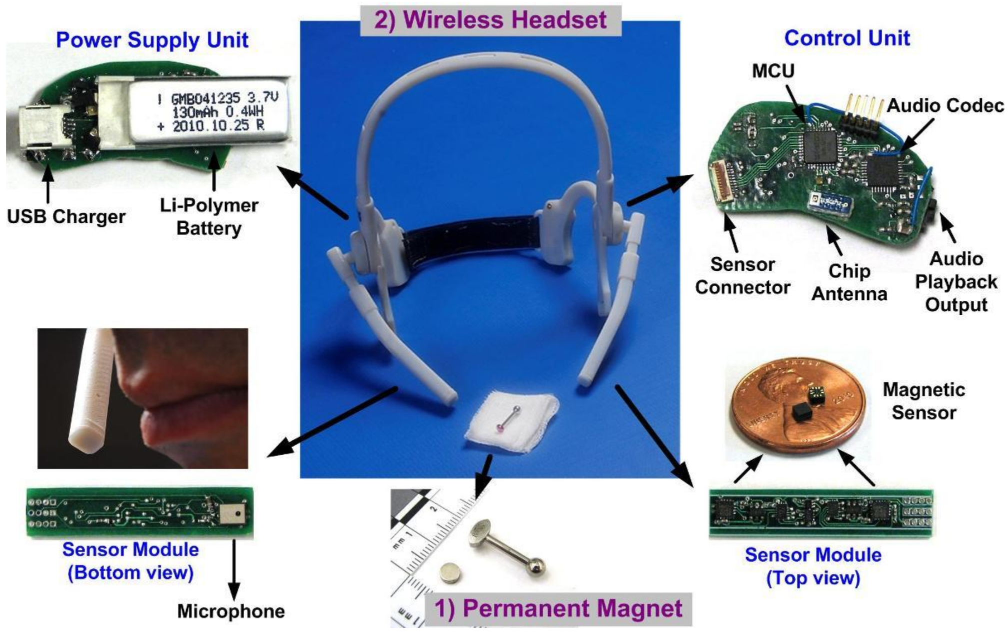
8.2 Multimodal Tongue Drive System (mTDS)

The mTDS, which block diagram is shown in Figure 8.1, operates based on the information collected from two independent input channels; the free voluntary tongue motion and speech, each of which is processed independently but then fused together at the end to generate a rich set of user-defined commands for a variety of tasks, user conditions, and environments [90].

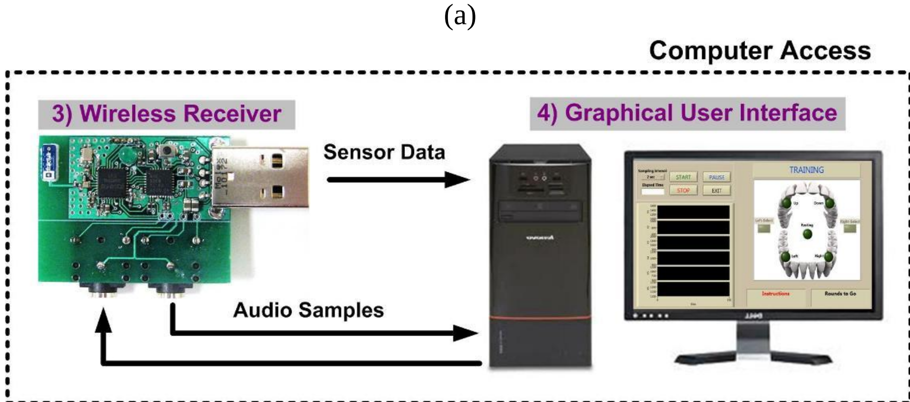
The primary modality of the mTDS is based on tracking the free voluntary tongue motion in the 3D oral space using a small magnetic tracer attached to the tongue via piercing, implantation, or adhesives, and an array of magnetic sensors (similar to the original TDS). The secondary input modality is based on the user's speech, which is captured using a microphone and wirelessly transmitted to the PC through the same wireless link used for communicating magnetic sensor data. The tongue-based primary modality is always active during the operation of the mTDS and regarded as the default input modality. The tongue commands resulted from the TDS modality is also used to interact with the graphical user interface (GUI) to enable and disable speech-based secondary modality without caregivers' assistance. To reduce power consumption of the system and extend the battery lifetime, the speech modality can be selectively turned on/off depending on whether it is needed or not using tongue motions. In this system, both TDS and speech recognition modalities are simultaneously accessible to the users, particularly for mouse navigation and typing, respectively. Users have the flexibility to choose the mode they want to use for any specific task without external assistance.

8.3 mTDS Prototype

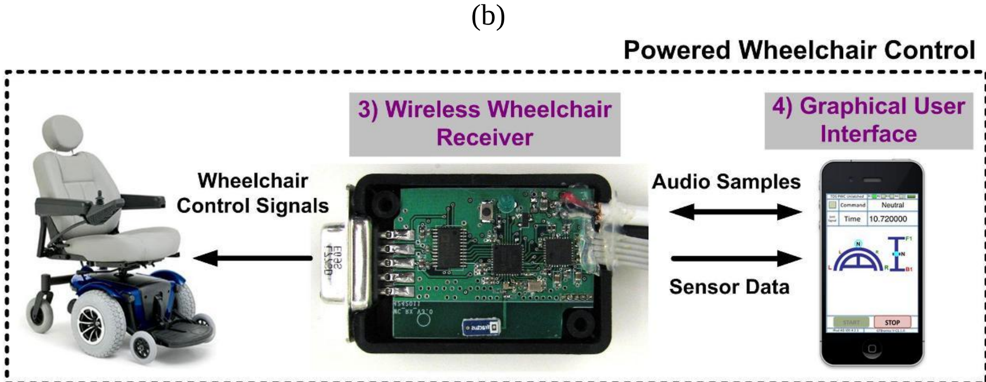
The latest mTDS prototype which is built on a customized wireless headset is an enhanced version of original TDS with the necessary hardware for a two-way wireless audio link to acquire and transmit users' vocal commands, as well as providing them with auditory feedback through a plug-in earphone. Figure 8.2 shows the main components of the latest mTDS prototype, including: 1) a small permanent magnetic tracer attached to the tongue using tissue adhesives or embedded in a titanium tongue stud for users who have tongue piercing, 2) A custom-designed wireless headset, which has been fabricated through 3D rapid prototyping and mechanically supports an array of 4 magnetic sensors and a microphone plus their interfacing circuitry to detect the tongue motion and record the voice, and a control unit to fuse and assemble into packets all the acquired raw data samples before wireless transmission, 3) A wireless transceiver unit that wirelessly receives the data packets from the headset and delivers them to the PC or smartphone,



(a)



(b)



(c)

Figure 8.2: The major components of multimodal Tongue Drive System (mTDS): (a) The permanent magnetic tracer and wireless headset, (b) The USB wireless transceiver and GUI for computer access, and (c) The wireless transceiver and GUI for PWC control.

and 4) A GUI running on the PC or smartphone that includes high throughput data communication drivers and SSP algorithm to identify the position of the magnetic tracer within the oral space and interact with a commercial speech recognition software .

8.3.1 Permanent Magnetic Tracer

A small (Ø3mm × 1.6 mm) disc-shaped rare earth magnet (K&J Magnetics, Jamison, PA) with high residual magnetic strength (B_r = 14,800 Gauss) was used as the tracer. Using small tracers is desired to minimize any possible discomfort and reduce the potential impact on the user's speech from the magnet attachment, which is important in achieving high accuracy when using mTDS with commercial speech recognition software. The higher B_r can compensate for the signal-to-noise (SNR) degradation in the magnetic sensor output due to shrinkage of the magnet tracer size.

8.3.2 Wireless Headset

A customized stylish wireless headset has been designed and fabricated to house and mechanically support the electronic components of the mTDS [127]. The main focus of this design was to combine aesthetic aspects with the user comfort, mechanical strength, and stable positioning of the sensors. The headset was designed in a way to also provide flexibility and adjustability to adapt to the user's head anatomy, while enabling proper positioning of the magnetic sensors and the microphone near the user's cheeks. The headset was first modeled in the SolidWorks (Concord, MA) environment and then fabricated from VeroGray resin (Objet, Billerica, MA) using 3D rapid prototyping machine Eden 250 at Georgia Tech Invention Studio [128].

The headset, the block diagram of which is shown in Figure 8.3, has a pair of adjustable sensor poles, each of which holds a pair of 3-axial magneto-impedance sensors

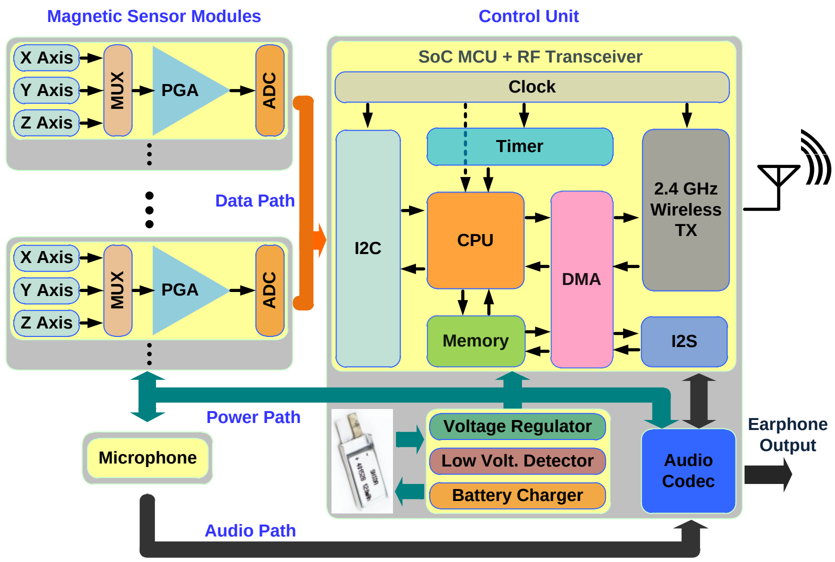


Figure 8.3: The block diagram of the multimodal Tongue Drive System (mTDS) wireless headset.

AMI306 (Aichi Steel, Tokai, Japan) [129] near the subjects' cheeks, symmetrical to the sagittal plane (Figure 8.2a). The magneto-impedance sensor makes use of the giant magneto-impedance effect, in which the ac impedance of sensing element, i.e. a magnetic amorphous metal wire, changes in response to the strength of the magnetic field [130]. Each AMI306 sensor consists of three sensing elements arranged in orthogonal configuration to measure the magnetic field vector in 3-D. It also integrates an on-chip magnetic signal readout circuitry, a programmable gain amplifier, a 12-bit analog-to-digital converter (ADC), and an Inter-Integrated Circuit (I2C) serial interface. The digital magneto-impedance sensor features higher signal-to-noise ratio, higher noise immunity, simpler interface circuitry, smaller form factor, and competitive power consumption compared with the magneto-resistive sensor used in our previous TDS [120]. In the mTDS, a low-power microcontroller (MCU) with built-in 2.4 GHz RF transceiver (CC2510, TI, Dallas, TX) communicates with each sensor through the digital I2C interface to perform measurement at 50 Hz, while turning on only one sensor at a time to save power. Each sensor consumes ~0.3 mA current when it is sampled at 50 sps. After all four sensor outputs are sampled, the results are packed into one data frame ready for RF transmission.

The acoustic signal acquisition is managed independent of the magnetic signal by an audio codec TLV320-AIC3204 (TI, Dallas, TX), through the built-in inter-IC sound (I2S) interface of the CC2510 MCU [126]. A miniaturized SiSonic MEMS microphone (Knowles, Itasca, IL) was placed near the tip of the right sensor board, as shown in Figure 8.2a, to continuously capture the acoustic signal when the user is speaking. The microphone is directly connected to the audio codec on the control unit which has dedicated power supply, ground, and signal wires to minimize the interference from digital control lines. The audio codec is programmed to operate at the lowest performance level with single-ended mono input, 8 kbps sampling rate, and 16 bits of resolution to minimize power consumption. This configuration provided sufficient quality to capture the voice signal in the frequency range of 100 ~ 2000 Hz using the SiSonic microphone with 59 dB SNR.

Digitized audio samples are read by the MCU through I2S and compressed to an 8 bit format using the CC2510 built-in μ-Law compression hardware to save the RF bandwidth. Due to the time critical nature of streaming audio, the audio data transfers within the MCU, from I2S to RAM and from RAM to the RF transmitter, are accomplished using direct memory access (DMA) to minimize the CPU intervention and the resulting latency. Once a completed audio frame (54 samples) has been acquired, in 6.75 ms, the MCU assembles an RF packet containing one audio and one data frame and transmits it wirelessly. Since the audio and data frames are generated at different intervals (6.75 ms vs. 20 ms), only one out of every three RF packets contains both audio and data samples, and the other two include only audio samples. These two types of packets are tagged with different preambles so that they can be recognized and properly disassembled on the receiver side.

After sending each RF packet out, the MCU expects to receive a back telemetry packet including one complete data frame and one optional audio frame, which depends on whether the uplink audio channel from the transceiver to the headset has been activated or not. The data frame contains the control commands from the PC or smartphone to switch on/off the speech modality. The audio frame in the back telemetry packet contains digitized sound signals from the PC or smartphone. The MCU extracts the audio samples from the back telemetry packet and sends them to the playback DAC of the audio codec through I2S interface to generate analog audio signals that are audible to the users if they attach an earphone to the designated audio jack on the dTDS headset. In the CC2510 MCU we have used a maximum RF data rate of 500 kbps, which is sufficient for bi-directional data and audio transmission.

A simple but effective wireless handshaking mechanism is implemented on both headset and the wireless receiver to establish a dedicated wireless connection between two devices so that their operations are not interfered by other nearby mTDS headsets. When the mTDS headset is just turned on, it enters the initialization mode by default and broadcasts a handshaking request packet containing specific header and its unique network ID using a basic frequency channel (2.45 GHz) at 1 s time intervals for one minute. If the headset receives a handshaking response packet back from a nearby mTDS transceiver within this one minute initialization time frame, it will update its frequency

Table 8.1: Multimodal Tongue Drive System Hardware Specifications

Specification	Value
Magnetic Tracer	
Material	NdFeB rare-earth magnet
Size (diameter and thickness)	∅ 3 mm × 1.6 mm
Residual magnetic strength	14500 Gauss
Magnetic Sensors	
Type	Aichi Steel AMI306 MI sensor
Dimensions	$2.0 \times 2.0 \times 1.0$ mm^3
Sensitivity / range	600 LSB/Gauss / ±300 μT
Microphone	
Type	SiSonic SPM0408HE5H
Dimensions	$4.7 \times 3.8 \times 1.1$ mm^3
Sensitivity / SNR	-22 dB / 59 dB
Control Unit	
Microcontroller	TI – CC2510 SoC
Wireless frequency / data rate	2.42 GHz / 500 kbps
Sampling rate / # of sensors	50 sample/s/sensor / 4
Audio codec / interface	TLV320AIC3204 / I2S
Audio sampling rate / resolution / compression	8 ksps / 16 bits / μ-Law
Operating voltage / current	3.0 V / ~ 35 mA (audio on) ~ 6 mA (audio off)
Dimensions	36×16 mm^2
Headset	
Material	Object VeroGray resin
Total weight	90 g (including battery)

channel, standby threshold, and other operating parameters which are extracted from the response packet. Then it sends an acknowledgement packet to the receiver to confirm the handshaking. After that, the mTDS headset switches to the normal operating mode with updated channel frequency and other parameters. Otherwise, the headset will enter the standby mode and blinks a red LED light located on the back of the headset to indicate that the initialization has not been successful, and the power cycle should be repeated.

The power management circuitry includes a miniaturized 130 mAh Lithium-Polymer battery, a voltage regulator, a low voltage detector, and a battery charger. The system consumes about 6 or 35 mA current at 3 V supply when the bi-directional audio channel is off or on, respectively. This allows the user to use the system continuously for about 20

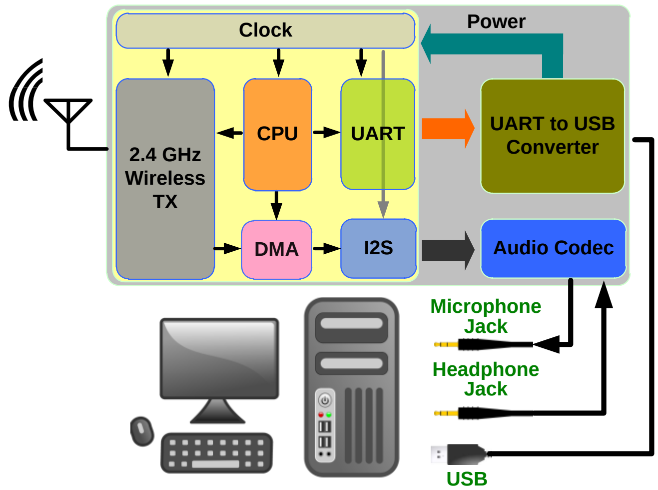


Figure 8.4: The block diagram of mTDS wireless USB transceiver for computer access.

or 4 hours in unimodal TDS or mTDS modes, respectively. Table 8.1 summarizes some of the key features of the current mTDS prototype.

8.3.3 Wireless Transceiver

Two new wireless transceivers prototypes have been built for the mTDS to interface with computers, smartphones, and powered wheelchairs (PWC).

A) Wireless USB Transceiver

The first type of transceiver is in the form of a USB dongle for computer access. Figure 8.2b shows a prototype of such transceiver equipped with a USB port and two audio jacks to communicate sensor data and audio signal with a PC, respectively. The block diagram of this USB transceiver is shown in Figure 8.4. The same type of MCU (CC2510) and audio codec that were used in the mTDS headset are used on this USB transceiver also, which has three operating modes: initialization, data transceiver, and file transfer. Switching between different modes is controlled by specific commands sent from the computer.

In initialization mode, the transceiver first listens to monitor any incoming handshaking request packets from a nearby mTDS headset. If the transceiver receives a handshaking request packet with an appropriate header and a valid network ID, it will scan through all the available frequency channels, and chooses one with fewer collisions as the optimal communication channel for that specific headset. The transceiver then switches to transmit mode and sends a handshaking response packet to the headset, which includes the assigned frequency channel and several other important operational parameters. The transceiver then switches back to receiver mode and waits for the confirmation via an acknowledgement packet. If an acknowledge packet is received within a specific time frame (5 s), the transceiver will update its frequency channel to the same frequency as the mTDS headset channel and enters data transceiver mode to receive regular sensor and audio packets. Otherwise, the transceiver will notify the computer that the handshaking has failed.

When the transceiver is in data transceiver mode, it works like a bi-directional wireless gateway to exchange data and audio samples between the mTDS headset and computer. It receives the RF data packets from the headset, extracts magnetic samples, and delivers them to the computer through the USB port. The audio samples, however, are streamed to a playback audio codec through the I2S interface and converted to analog audio signals, which are then applied to the microphone input of the computer through a 3.5 mm audio jack (see Figure 8.2b). The transceiver can also receive analog audio outputs from the computer headphone jack through a similar 3.5 mm audio jack and digitize them using the same audio codec and I2S interface that are used to process the playback sound.

Alternatively, the transceiver can receive the audio samples in digital format directly through the USB connection from the computer. Similar to the mTDS headset, these audio samples are compressed using CC2510 built-in μ-law compression hardware, packaged into an audio frame and wirelessly transmitted to the mTDS headset. The transceiver also receives data packets from the computer, which contain the mTDS operating parameters, used to program the mTDS headset in real time. The data packet is combined with the audio frame to form a back telemetry RF packet which is then wirelessly sent back to the headset.

The third mode of the USB transceiver, file transfer mode, is meant to wirelessly transfer user-specific information from the computer to a smartphone, such as iPhone. Similar to computer access, in order to use the smartphone with the mTDS, users need to customize the tongue commands for this specific device based on their preference, life style, and remaining abilities through a training process, which yields a set of user-specific training data files. Users can perform the training steps either on the computer or directly on the smartphone (iPhone). Perhaps conducting the training steps on the computer is preferable and more convenient due to access to a larger screen. After the training files are generated on the computer, they can be wirelessly transferred to the smartphone and then used for controlling the PWC or other mobile applications that are performed on the smartphone without requiring them to go through yet another training step. In this case, the USB transceiver can be switched to the file transfer mode, in which it operates as a transmitter and wirelessly transmits the user-specific files that it receives from the computer to the smartphone transceiver.

B) PWC-Smartphone Transceiver

The second type of wireless transceiver is designed for PWC, smartphone, and environmental control in a mobile setup. Figure 8.2c shows a prototype wireless

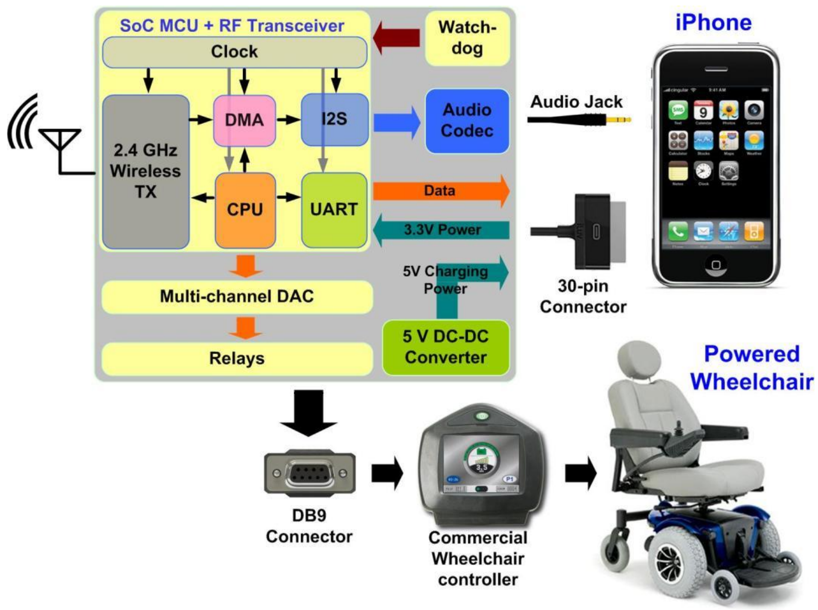


Figure 8.5: The block diagram of mTDS wireless PWC-iPhone transceiver.

PWC-Smartphone transceiver that has been developed and tested with an iPhone and a commercial PWC Q6000. The transceiver is attached to an iPhone via its 30-pin charging connector and communicates with the mTDS headset using the same mechanism as the PC-based USB transceiver. In addition, the transceiver provides multiple channels of analog output signals to control a PWC through its dedicated 9-pin D-type (DB-9) universal port. Figure 8.5 shows the block diagram of the PWC-iPhone transceiver. The circuitry of the PWC-iPhone transceiver includes a low power microcontroller with RF capability (CC2510), a digital-to-analog converter (DAC), an audio codec, a battery charging circuit, a watchdog timer, and two normally open relays. The transceiver is connected to the iPhone through a standard 30 pin interface and uses the RS-232 serial communication protocol to exchange data back and forth with the iPhone. During normal operation, data packets that are wirelessly sent by the mTDS headset are received by the transceiver and sent to iPhone through serial port for further sensor data extraction and processing. The SSP algorithm, which has been migrated from PC to the iPhone, interprets the commands issued by the users based on the received sensor data. When the target device is the PWC, these commands are used to modify the speed and rotation vectors that are associated with the PWC's linear speed and rotation rate. State vectors are then sent from iPhone to the PWC-iPhone transceiver to be converted to multichannel analog signals that are compatible with the PWC universal controller using an off-chip digital-to-analog converter, AD5724 (Analog Device, Norwood, MA), driven by the CC2510 microcontroller. These analog signals that are in the range of 4.8 – 7.2 V are applied to the PWC universal control unit through its DB-9 connector to control the wheelchair movements. Considering the PWC supply voltage might be slightly different among the chairs from different vendors (11.5 ~ 12.5 V), one of the CC2510 on-chip ADC channels is utilized to measure the exact value of the PWC supply voltage after it is down-converted below 3V using a resistive divider. The measurement results are used to regulate the reference voltage that is applied to the PWC universal control unit to determine the stationary condition of the chair.

The PWC-iPhone transceiver also includes a playback audio codec to convert the wirelessly received digital audio samples to analog sound signals, which are then applied to the microphone input of the iPhone 3.5 mm audio jack. The input speech signal can be used with iPhone built-in speech recognition engine for voice dialing or used with third party applications (such as Avoca VIP Control4) for environmental control. This audio codec can also receive the audio signals from iPhone and convert them into digital samples that can be wirelessly transmitted back to the mTDS headset through the same wireless link. This bi-directional audio link between mTDS headset and iPhone allows the user to directly use the mTDS headset as a hands-free wireless headset to make and receive phone calls without requiring any additional audio input/output device, such as a Bluetooth headset.

To improve safety, a watchdog timer function, similar to that mentioned in section 4.3.2, is added to the PWC-iPhone transceiver. Basically, if the wireless link is broken due to a malfunction in the mTDS or electromagnetic interference, the watchdog function is triggered and it will reset the MCU to bring the PWC to a standstill. Additional safety feature is introduced by adding normally open relays between the DAC outputs and the commercial PWC universal control unit. The relays are closed by the microcontroller to route the DAC outputs to the PWC control unit in the normal operating conditions. If the MCU is malfunctioning or the power is lost due to disconnection of the transceiver from the iPhone, the relays will automatically switch to open-circuit and disconnect the DAC outputs from the PWC driver, as if the PWC control unit has not been connected to any external devices. In this case, the built-in safety mechanism of the PWC universal control unit will immediately stop the chair. This can prevent the PWC from being locked in certain condition when any malfunction or freeze occurs in the MCU or the smartphone.

The PWC-iPhone transceiver receives its power from two sources: First from the 12 V supply pin available in the DB9 PWC universal port, and second from the 3.3 V iPhone power supply available from in the 30 pin connector. The 12 V PWC power supply is mainly used to power the analog part of the DAC and the relays, while the rest of the interface circuits are powered by the 3.3V iPhone supply. In such configuration, even if the PWC is off, the MCU, RF and audio codec circuitry maintain power and continue operating as usual. Therefore, users can still use the mTDS to access all the functions available on the smartphone (iPhone) such as making a phone call, checking contacts, and surfing the internet. A DC-DC converter, LT3653 (Linear Technology, Milpitas, CA), converts the 12 V PWC voltage down to 5 V, which has been used to charge the iPhone through its 30 pin connector from the large PWC batteries.

Similar to the PC USB transceiver, the PWC-iPhone transceiver has three operating modes. The first mode, which is the initialization mode, is exactly the same as the USB transceiver and it is used to establish a one-to-one connection between the mTDS headset and the PWC-iPhone transceiver. In the data transceiver mode, the difference between the USB transceiver and the PWC-iPhone transceiver is that the latter has been equipped with an additional DAC to convert digital commands that are detected by the SSP algorithm and used to modify the PWC linear and rotation vectors into analog voltage levels to control the PWC motion. In the file transfer mode, the PWC-iPhone transceiver is configured as a receiver to receive the user-specific trainings files and send them to the iPhone, which in turn saves the files and uses them to detect control commands during mTDS operation.

8.3.4 Graphical User Interface (GUI)

The same SSP algorithm and GUIs that were used in previous eTDS prototypes can be used in the mTDS to detect the tongue motion based TDS commands for computer access applications. In addition, the SSP algorithm has been migrated from PC to iPhone and a new set of GUIs have been developed on iPhone platform to allow the users to control wheelchairs and their environment in a mobile setup. However, the development of iPhone application is out of the scope of this thesis and will not be discussed here.

Any piece of commercially available or customized speech recognition software that works with a regular microphone can be used with the mTDS hardware, because the audio signals are directly applied to the microphone input of the computer or smartphone. Dragon Naturally Speaking (Nuance, Burlington, MA) was our choices in this prototype since it has been widely used by the disability community and supports a wide variety of platforms (Windows, Mac, iPhone, etc.).

8.4 Summary

In this chapter, we have presented the concept of multimodal Tongue Drive system (mTDS), which uses tongue motion and speech recognition as its primary and secondary input modalities, respectively. By expanding the number of the communication channels, the mTDS allows people with severe disabilities to interact with their environment with increased speed, flexibility, and independence compared with its unimodal counterparts. The latest mTDS prototype, which is built on a customized wireless headset, is an enhanced version of original TDS with the necessary hardware for a two-way wireless audio link to acquire and transmit users' vocal commands, as well as providing them with auditory feedback through a plug-in earphone. It can detect up to six user-defined tongue commands, as original TDS, with the addition of speech recognition capabilities, which is expected to be a good complementary to TDS, especially for text entry in computer access.

CHAPTER IX

MULTIMODAL TONGUE DRIVE SYSTEM PERFORMANCE EVALUATION

The multimodal Tongue Drive System (mTDS) provides people with severe disabilities with more than one channel to communicate with their environment, therefore allowing them to control devices in their environments, particularly a computer, with increased speed, flexibility and independence. To evaluate the mTDS performance in computer access, we recruited 14 able-bodied subjects to participate in a trial, which required them to perform a set of comprehensive computer access tasks that involved both mouse cursor navigation and typing using the two modalities of the current mTDS prototype, i.e. the tongue motion and speech recognition, both individually and concurrently.

9.1 Subjects

Fourteen able-bodied subjects (9 males and 5 females) were recruited from the Georgia Tech graduate and undergraduate student population. Their average age was 26.7 years old, with a range between 21 to 30 years old (*SD* = 3.0). Seven subjects had prior experiences with TDS, either as a member of the research team or because of having participated in the previous TDS-based studies. However, none of them were regular TDS users. The other seven subjects were completely new to TDS (naive subjects). Two subjects had several hours (<10) of prior experience with the Dragon, and others had never used the Dragon software before. There were an equal number of native (7) and non-native (7) English speakers in our subject pool. The necessary approval was obtained from the Georgia Tech's Institutional Review Board (IRB) and informed consent forms were collected from all subjects prior to the experiments.

9.2 Experimental Design

The experiment was divided into two sessions; practicing session and experimental session, with maximum of one week gap in between. In the practicing session, subjects learned how to use the Dragon software and mTDS, and familiarized themselves with the contents and flow of the experiment by going through all the experimental tasks only once, with no repetition. During the experimental session, the subject performed and repeated all the tasks except the text transcription (explained in section 9.2.1) for four times with different mTDS modalities. Each session took about 3 hours.

9.2.1 Text Transcription

The purpose of the text transcription task was to evaluate the performance of the mTDS wireless microphone, which was incorporated in the mTDS headset, and to compare it with a commercial microphone that was designed specifically for the speech recognition software. This experiment was only repeated once in the practicing session, and no TDS function was needed while performing this task.

At the beginning, the subjects received basic instructions on how to use the Dragon Naturally Speaking speech recognition software in the case they had not prior experience with the software. Then, they trained the Dragon by reading 10 short paragraphs provided by the manufacturer using both the wireless microphone function incorporated in the mTDS headset and a commercial microphone, NC-181VM (Andrea Electronics Corporation, New York, NY). Afterward, the subjects were asked to transcribe two standard paragraphs of text (~120 words each) from a hardcopy to a word document via dictation utilizing both microphones, together with the Dragon software. The selected

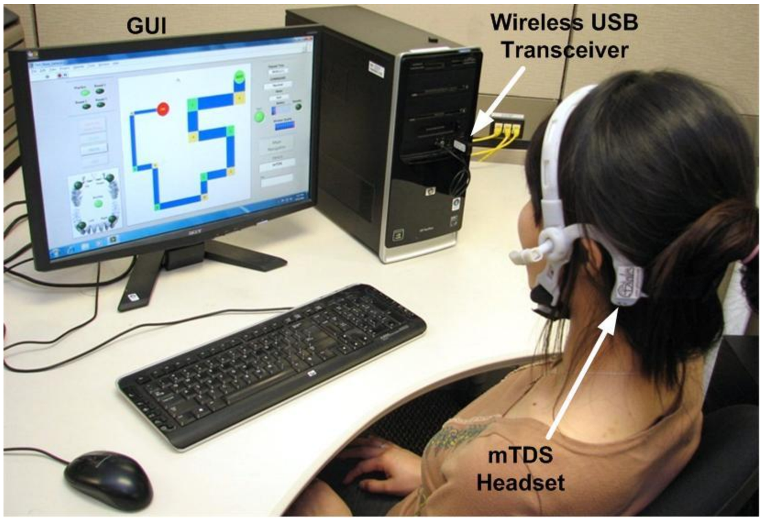


Figure 9.1: mTDS experimental setup: one subject wore the mTDS headset and sat ~1m from a 22” monitor during a maze navigation task.

paragraphs, *The North Wind* and *the Sun and The Grandfather Passage*, are commonly used for examining speech recognition software [132]. The subjects were asked to dictate in their regular speed and not to correct any errors. The results were used to calculate the recognition accuracy for each specific input device.

9.2.2 Comprehensive Computer Access

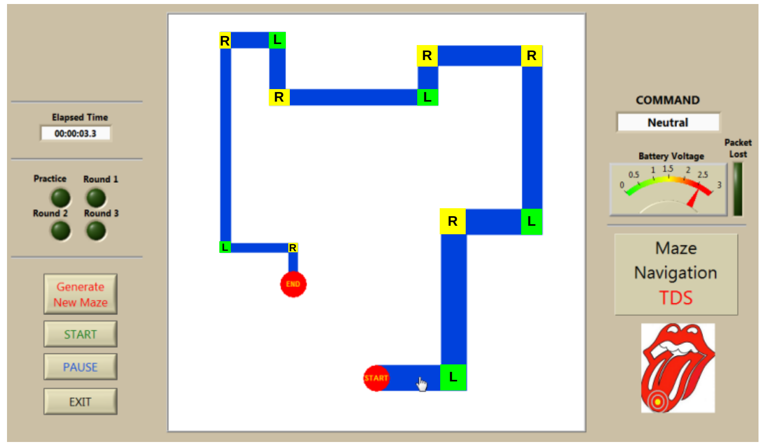
The purpose of these experiments was to compare the performance of the mTDS in completing comprehensive computer access tasks that involved both mouse cursor navigation and typing with its unimodal counterparts (TDS and Dragon). A within-subject model was designed with each subject repeating the tasks using three devices, i.e. TDS, Dragon, and mTDS.

During the experiments, the subjects had a small permanent magnet temporarily attached to their tongue using tissue adhesive, worn an mTDS headset to detect their tongue motion and speech, and sat ~1m from a 22” monitor with 1280×800 resolution (Figure 9.1). They went through the TDS calibration, command identification, and training steps as explained in section 5.2 to define the mTDS tongue commands. In the practicing session, subjects started with two-command training and practicing, then the number of tongue commands was increased from two to four and eventually to six in order to help subjects learn how to use the TDS step-by-step from easy to advanced tasks. In the experimental session, subjects started the session by defining and training the TDS with six tongue commands, which were used to navigate the mouse cursor in the cardinal directions and issue left and right mouse clicks.

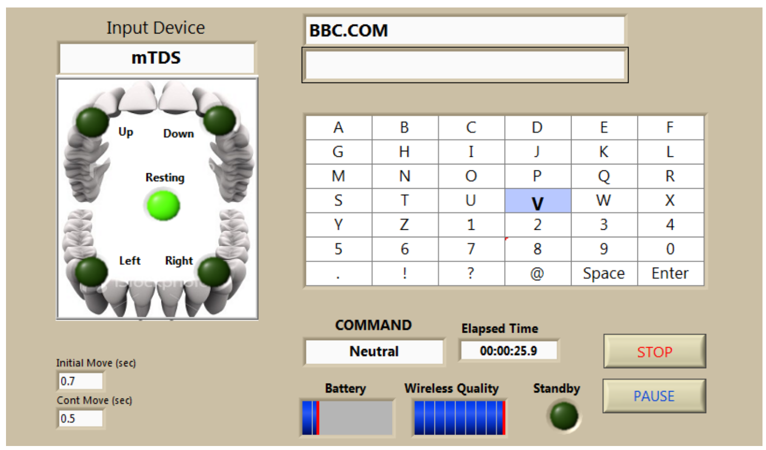
After both Dragon and TDS have been trained and practiced, the subjects were asked to complete a set of comprehensive computer access tasks, which involved both mouse cursor navigation and typing. For instance, the subjects were required to navigate mouse cursor through an on-screen maze while being asked to type after left/right clicking on certain icons in the maze. They were also instructed to complete a modified ISO9241-9 standard [118] center-out tapping task in which the target clicking was randomly interleaved with typing tasks.

A) Maze Navigation

In the maze navigation experiment, subjects were instructed to move the cursor as quickly and as accurately as possible through an on-screen maze (Figure 9.2a) from the START red circle to the END red circle. As accurately as possible means keeping the cursor within the blue track and avoiding the white background. At the beginning of each trial, the mouse cursor was automatically positioned in the center of the START cycle and the subjects were instructed to move the cursor after they saw the red START circle turned into green. The experiment automatically terminated when the subjects moved the cursor within the END circle. During navigation, subjects were also required to stop at the check points and issue either a Left or Right select command according to the color and associated letter



(a)



(b)

Figure 9.2: The GUIs of the modified maze navigation experiment: (a) Navigation GUI, and (b) Typing GUI.

inside that specific check point (Left: Green-L, Right: Yellow-R). The color of the check point turned to gray upon selection to indicate that the subjects had correctly issued the designated select command within that check point. Out of eleven check points, four of them were randomly selected and associated with typing tasks. After the subjects clicked on such a check point, a typing window, shown in Figure 9.2b, popped up and the subjects were asked to type a short phrase shown on the top of the window as quickly and accurately as possible. The typed characters appeared in a textbox below the target phrase for further comparison. The subjects should correct the typing errors only when they made mistakes, but ignore the system related errors, such as the recognition errors made by Dragon. Four different types of phrases, including common phrases, websites, phone numbers, and spelled words, appeared one at a time in a randomized order in each round. Overall, the subjects had to complete a minimum of 12 mouse cursor movements, 11 mouse clicks (excluding those for typing with TDS), and average 36 typed-in characters in each round of trial.

B) Modified Center-out Tapping

The subjects were also required to perform a modified ISO9241-9 standard [118] center-out tapping task, in which the target clicking was randomly interleaved with typing tasks. ISO9241-9, which is based on the well-known Fitts' law [117], has been widely adopted by the human computer interface (HCI) community for evaluating conventional non-keyboard input devices as well as ATs such as eye trackers [133], head trackers [134], and voice activated software [135]. A key parameter in this standard is *throughput*, measured in bits/s as an indicator for the amount of information that users can deliver to a computer through the device under test. ISO9241-9 standard shows how to calculate the throughput in certain tasks of rapid movements over on-screen targets of different sizes and distances with the purpose of emulating human interactions with Graphical User Interfaces (GUI).

In this modified center-out tapping task, circular targets with three different diameters (W = 30, 61, and 122 pixels) and three different distances from the center of the screen (D = 61, 122, and 244 pixels) created a total of six D-W pair. They appeared randomly on the screen one at a time along cardinal and ordinal directions (every 45° from the center), forming a total of 48 (6×8) targets, as shown in Figure 9.3, similar to that reported in

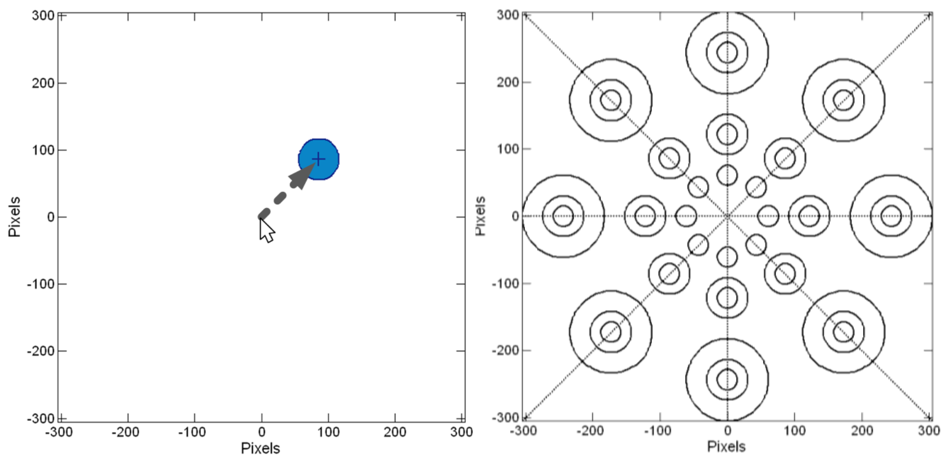


Figure 9.3: The GUI of mTDS rapid center-out tapping task with all 48 possible target conditions on the right panel.

[120]. These 48 targets were evenly distributed into three testing rounds of experiment, resulting in 16 targets associated with two D-W pairs in each round. The subjects were instructed to move the mouse cursor from the center of the screen towards the targets as soon as they observed the appearance of the targets. They were also instructed to move the cursor as fast and as close to the center of the targets as possible, and issue a left select command to confirm the selection. Four out of sixteen targets in each round were randomly selected and associated with typing tasks. The subjects should complete the typing tasks in the same way described in the maze navigation (a) session.

Subjects were required to complete the tasks using the TDS alone, Dragon alone, and mTDS (the combination of TDS and Dragon). During the experimental session, all tasks were repeated four times for each variation, one for practice followed by three testing rounds. When using the TDS, the microphone was turned off to deactivate the Dragon. In this case, the directional TDS commands were used to move the cursor on the screen in four directions and the selection commands were used to issue mouse left-click and right-click. Typing was accomplished by navigating a cursor on a standard on-screen keyboard, shown in Figure 9.2b, to highlight a desired character using directional commands, and then entering that character by issuing a left-select command. Right-select in this case was used as backspace to erase the last entered character.

When using Dragon, the TDS function was disabled. A set of predefined verbal commands, such as “move mouse Left/Right/Up/Down”, “move mouse slow”, “much faster”, and “left/right select”, were used to move the cursor and issue mouse clicks by dictating those commands. In the mTDS mode, both the TDS and Dragon were active and subjects were required to use the tongue commands (TDS) for mouse navigation and clicks, and verbal commands (Dragon) for typing. The order of using each device was randomized to minimize the learning effect. At the end, the subjects were also asked to perform the same tasks with a combination of standard mouse and keyboard to generate a reference point.

9.2.3 Questionnaire

Once subjects completed all the tasks in the second session, they answered a questionnaire rating each device in different aspects, such as speed, accuracy, being easy-to-learn, fatigue, etc. They were also asked about their preferred input modality to access a computer if they were not able to use neither a mouse nor a keyboard.

9.3 Performance Measures

The performance measure for text transcription experiment was recognition accuracy, which was defined as the percentage of correctly recognized words to the total number of words included in the two text reading paragraphs.

For the maze navigation, the performance measures include total completion time, cursor navigation time, typing time, navigation error, and typing error. The first three timing measures indicate the speed of each input device in completing specific tasks, and were calculated from the recorded time during cursor navigation and typing. Navigation error, similar to section 7.3.3, is the summation of all the deviations of the cursor path from the edges of the blue track divided by 1000 as a measure of navigation accuracy. The typing error was calculated as the percentage of mistyped letters over the total number of letters to be typed during the typing tasks.

For the center-out tapping, in addition to total completion time, cursor navigation time, typing time, and typing error, as those defined in the maze navigation, two more performance measures including throughput and error rate were considered to assess the speed and accuracy in pointing and selecting.

Throughput (TP): shows the amount of information that subjects delivered to the computer through each of the input devices. TP is defined as the ratio between the *effective Index of Difficulty*, ID_e, of targets with the same condition (i.e. same D-W pair) to MT, the time it takes to reach them:

$$TP = ID_e / MT \tag{9.1}$$

where ID_e of the target, measured in bits, is defined by the Shannon's formula [136] as

$$ID_e = \log_2 \left(D_e / W_e + 1 \right) \tag{9.2}$$

$W_e = 4.133 \times SD_x$ is the *effective Width* for each condition, and SD_x is the standard deviation of x, which is the distance between the location that the subject points while reaching a target and the center of that target, when projected onto a straight line from the origin of the movement to the center of the target, known as the task axis [137], [138]. x can be positive or negative when the subject overshoots or undershoots during a pointing task, respectively. D_e, the *effective Distance,* is defined as the mean of the distances of the

Table 9.1: Indices of Difficulty in the Center-Out Tapping Task

Pixels		D1	D2	D3
		61	122	244
W1	30	1.60	2.34	3.19
W2	61		1.59	2.32
W3	122			1.59

pointed spots projected along the task axis over all the targets with the same condition. *MT* in (9.1) only includes the time when the cursor is moving, i.e. it neither includes the initiation delay time before the subject moves the cursor nor the selection time. With the above definition, *TP* bears both the speed and accuracy of the subjects' pointing performance. Table 9.1 shows the *IDs* for different D-W pair conditions. *ID* values are derived from (9.2) where actual D_s and W_s are inserted rather than D_{es} and W_{es}.

Error Rate (ER): is the percentage of the taps outside the targets to the total number of taps for each task. While *TP* does not reflect whether the targets were eventually selected or not, *ER* reveals the subjects' accuracy in using the computer input device for pointing and selecting the targets [119].

The reported performance measures of each device were calculated by first averaging within each individual subject across three testing rounds and then averaging across all 14 subjects. The 95% confidence intervals were also calculated to indicate the variations of each measure.

9.4 Results

9.4.1 Performance of mTDS Microphone

Subjects achieved an overall 87% and 84.5% recognition accuracy using the commercial and mTDS microphones, respectively (Figure 9.4). These results were lower than the accuracy claimed by Nuance (>95%) the manufacturer of Dragon Naturally Speaking

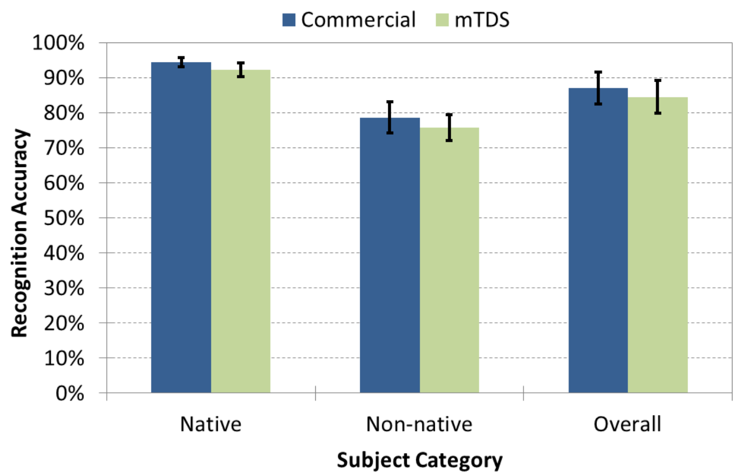


Figure 9.4: Average speech recognition accuracy of different microphones used by native and non-native English speaking subjects (Error bars show 95% confidence interval).

software. This is possibly because of the lower performance of the non-native English speakers who had accents and were unfamiliar with Dragon's diction pattern. We ran a Two-way analysis of variation (ANOVA) on recognition accuracy considering both device and English accent as factors. This analysis revealed that native speakers performed significantly better than non-native speakers (78.6% and 75.7% vs. 94.3% and 92.2% for commercial and mTDS microphones, respectively) with $p < 0.01$; while there was no evidence to claim difference between the performance of commercial and mTDS microphones. Dependency on the users' accents is one of the issues associated with unimodal voice control devices aside from their susceptibility to ambient acoustic noise.

9.4.2 Maze Navigation

Figure 9.5 shows the averaged total completion time, cursor navigation time, and typing time of three input devices mentioned above, plus mouse/keyboard combination as a reference point, in completing maze navigation experiment. One-way ANOVA conducted with device as a factor has shown significant effect of device on all three measures. Pair-wised comparison with Bonferroni adjustment revealed that the total completion time

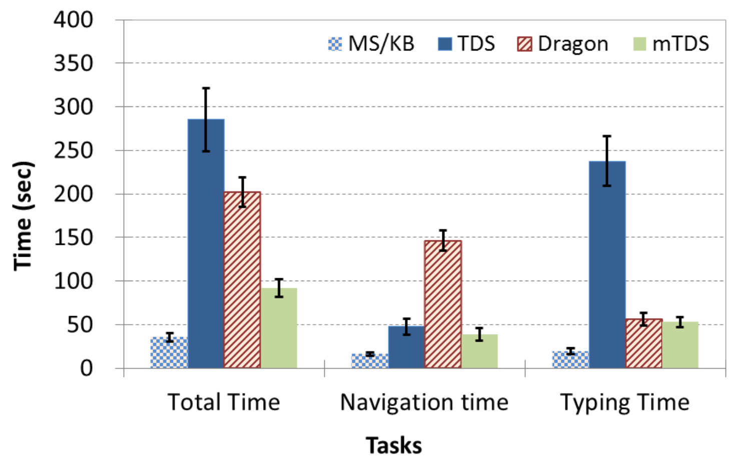
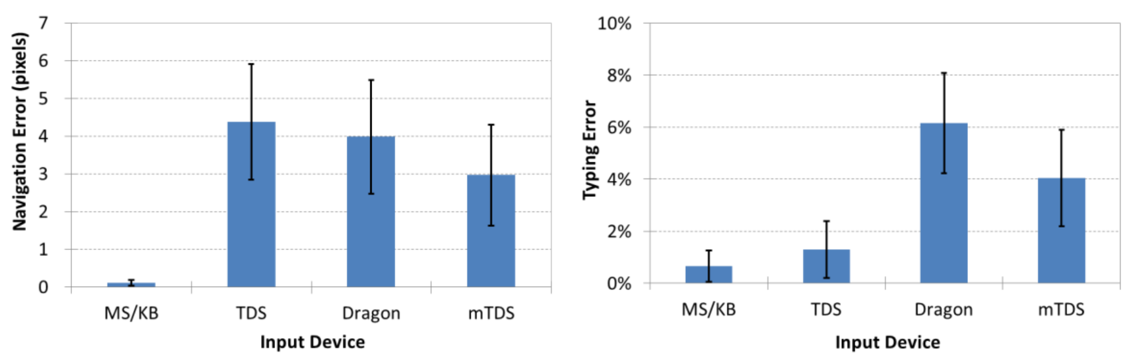


Figure 9.5: Average completion time in seconds by different devices in performing maze navigation experiment (Error bars show 95% confidence interval).



(a) (b)

Figure 9.6: Errors in maze navigation experiment: a) Average navigation error in pixels by different devices; b) Average typing error in percentage of mistyped letters. Error bars show 95% confidence interval.

of mTDS (92 s) was significantly shorter than those of TDS (285 s) and Dragon (202 s) alone, with $p < 0.01$ in both cases. Same analysis also showed that there were significant differences between all performance measures of unimodal TDS and Dragon (all $p < 0.01$). TDS outperformed Dragon in term of cursor navigation time (48 s vs. 146 s), while Dragon was much faster in typing (56 s vs. 238 s). No enough evidence was discovered to claim difference between the navigation time of the mTDS and TDS, no between the typing time of the mTDS and speech recognition. This shows that the TDS and speech recognition

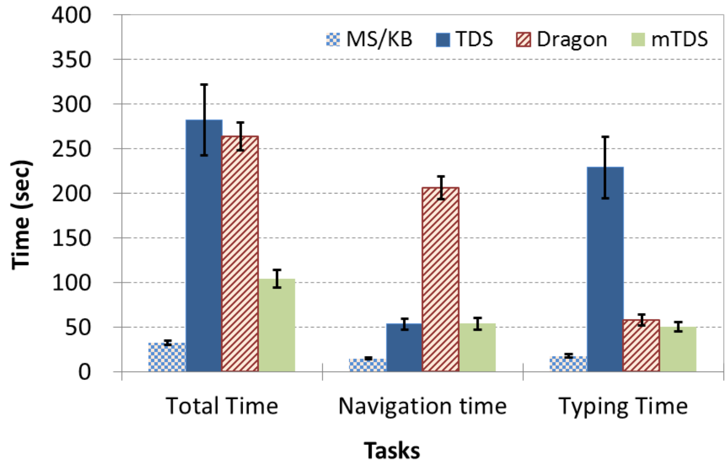


Figure 9.7: Average completion time in seconds by different devices in performing center-out tapping experiment (Error bars show 95% confidence interval).

(Dragon) can be used together in the mTDS without running the risk of degrading the user's performance due to their mutual interference.

Figure 9.6 shows the cursor navigation and typing errors using different devices in completing maze navigation tasks. We performed one-way ANOVA on both accuracy measures with device as a factor. Results showed that there was no significant difference among the navigation errors of different devices except for mouse/keyboard. The typing error of the TDS is significantly lower than that of Dragon and mTDS ($p < 0.01$), while there was no difference between Dragon and mTDS.

9.4.3 Center-out Tapping

Figure 9.7 shows the averaged total completion time, cursor navigation time, and typing time of all input devices in completing center-out tapping tasks. One-way ANOVA that conducted with device as a factor has shown significant effect of device on all three measures. Pair-wised comparison with Bonferroni adjustment showed that the total completion time of mTDS (104 s) was significantly shorter than those of TDS (282 s) and Dragon (264 s) alone, with the p-value < 0.01 in both cases. Same analysis also

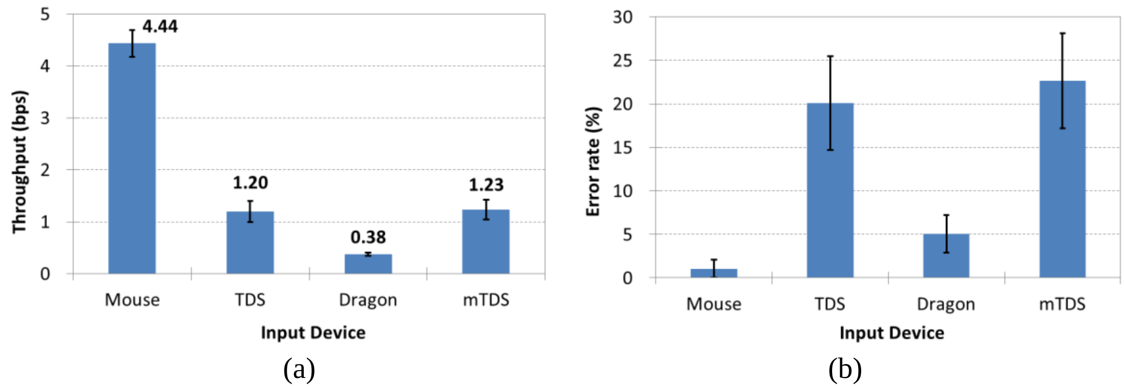


Figure 9.8: The pointing performance of different devices in completing center-out tapping tasks: a) Average throughput, and (b) Error rate. Error bars show 95% confidence interval.

demonstrated that there were significant differences between the cursor navigation time ($p < 0.01$) and typing time ($p < 0.01$) of unimodal TDS and Dragon, while there was no evidence to claim difference between the total completion of these two devices ($p = 0.954$). Similar to the maze navigation, TDS's performance was better in navigation, while Dragon was much faster in typing. No enough evidence was found to claim difference between the navigation time of the mTDS and TDS, no between the typing time of the mTDS and speech recognition. The total completion time of mTDS was also about three times that of mouse/keyboard combination.

Figure 9.8 shows the average throughput and error rate in completing tapping tasks in center-out experiment using different devices. The mouse *TP* (4.44 bits/s) is within the generally accepted range of 3.7-4.9 b/s [119], which validates our methodology, GUI functionality, and data analysis. One-way ANOVA considering device as a factor showed significant effect of device on both measures. Pair-wised comparison with Bonferroni adjustment showed that the throughput of both TDS (1.20 bits/s) and mTDS (1.23 bits/s) are significantly higher than that of Dragon (0.38 bits/s), while there was no evidence to

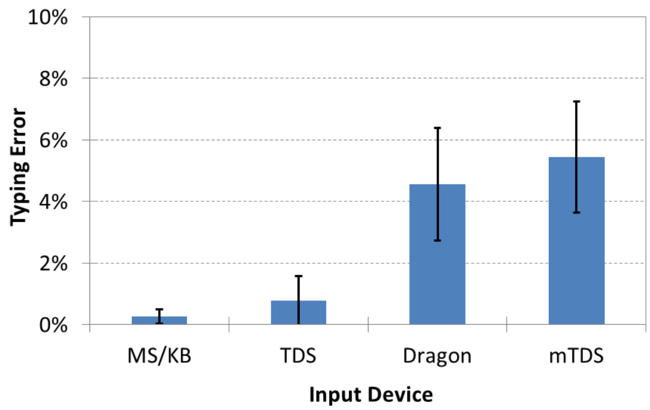


Figure 9.9: Average typing error in the center-out tapping experiment (Error bars show 95% confidence interval).

claim difference between the throughput of former two devices. Similar results were observed for the error rate as well. The error rates of TDS and mTDS were significantly higher than that of Dragon, but there was no enough evidence to claim difference between each other. The achieved TDS/mTDS throughput were consistent with our previously findings reported in [120].

Similarly, we performed one-way ANOVA on typing error with device as a factor. As it is visualized in Figure 9.9, the overall typing error of the TDS is significantly lower tthan that of Dragon and mTDS ($p < 0.01$), while there was no evidence to claim difference between the typing error of Dragon and mTDS.

9.4.4 User Perception

The users' subjective ratings on different devices are summarized in Figure 9.10. The response was in a scale of 1 to 9, with the higher number representing a more positive perception about that specific question. Statistical analysis (one-way ANOVA with pair-wised comparison) showed that mTDS received significantly higher ratings than the other two devices in terms of speed (both $p < 0.01$) and overall satisfaction (both $p < 0.01$).

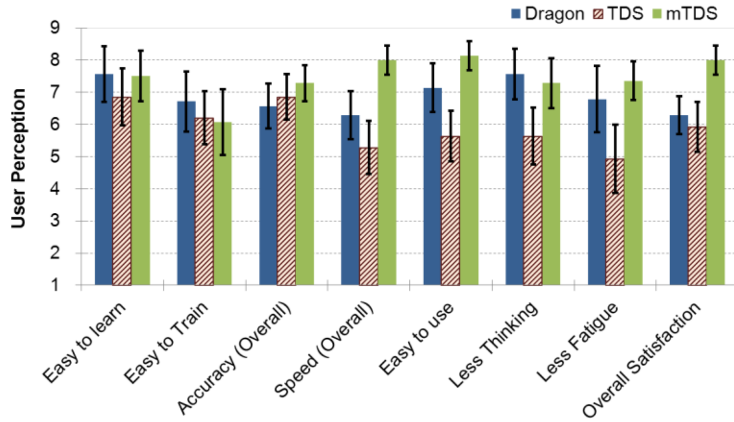


Figure 9.10: Users' answer to a post-session questionnaire. Higher number represents more positive perception (Error bars show 95% confidence interval).

There was no evidence to claim difference among devices as far as the perceived accuracy was concerned. These results were consistent with the quantitative measurements mentioned above. All subjects reported that they prefer to use the mTDS over TDS or speech recognition software if they were not able to use mouse and keyboard to access computers.

9.5 Discussion

The main purpose of this study is to compare the performance of TDS, speech recognition (Dragon) and mTDS in completing comprehensive computer access tasks, and discover the benefits of using mTDS over its unimodal counterparts. We also want to explore the strength and the weakness of each modality in the current version of mTDS. This information can be used to assist the potential users of mTDS in such a way that they will take best advantage of each modality to achieve maximum performance.

In both computer access tasks, the subjects performed consistently faster in cursor navigation and typing using TDS and Dragon respectively. The subjects obviously benefited from using both modalities. This is evident from the lowest total completion time that was achieved when using the mTDS which was only 32% and 46% of using the TDS alone or Dragon alone respectively in maze navigation, and 37% and 46% respectively in center-out tapping experiment. In addition, the total completion time of mTDS is only about three times that of mouse/keyboard combination in both experiments. This is quite significant considering that all subjects had much less experience in using mTDS compared to the mouse/keyboard combination, which they were using on a daily basis. It is reasonable to expect the difference between mTDS and mouse/keyboard to become smaller once subjects use the mTDS on a daily basis over an extended period of time.

Statistical analysis showed that there was no evidence to claim difference among the navigation errors of different devices in the maze navigation, while the error rate (out-hitting error) of Dragon was significantly lower than TDS and mTDS in performing tapping tasks in center-out experiment. This indicated that the Dragon and TDS are equally accurate in controlling mouse cursor to follow a designated path, while the Dragon seems to be more precise in pointing a specific target. However, it should be noted that the high pointing accuracy of Dragon was achieved at the cost of extremely low speed, which is evident from it long movement time and low *TP*. On the other hand, even though the pointing accuracy of TDS or mTDS was high at this stage, it is expected to decrease dramatically over time as a result of learning, which has been observed in section 7.3.4 and [120]. As a measure considering both speed and accuracy, the *TP* of TDS/mTDS is much higher than Dragon in center-out tapping. This demonstrated that the tongue motion based modality, in general, is a better option compared with speech recognition modality to control mouse cursor in computer access tasks.

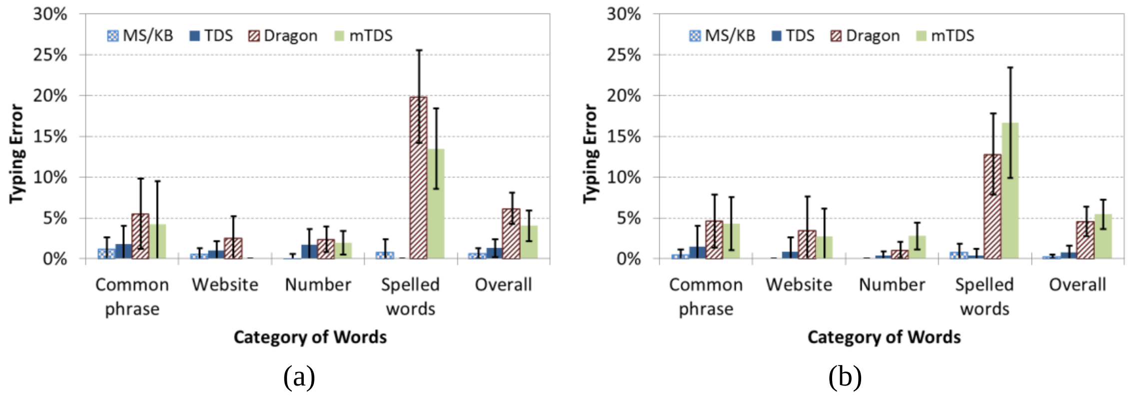


Figure 9.11: Average typing error associated with different type of words in a) maze navigation tasks, and b) center-out tapping tasks. Error bars show 95% confidence interval.

The typing errors in both experiments were categorized in terms of the types of words. As it can be seen in Figure 9.11, typing errors of Dragon and mTDS were especially high in the spelled words category. This seems to be reasonable since the degradation of speech recognition accuracy due to the subject's accent can be partially compensated if the dictated words or phrases have a certain pattern, such as when they are used in a sentence. On the other hand, spelling of the individual letters prevents the speech recognition software from recognizing their pattern in a word or in a sentence.

Overall, using the mTDS could significantly increase the speed in completing computer access tasks, but did not result in higher accuracy when considering both typing and navigation. This is mainly because of the large typing error rate associated with the speech recognition modality, which seems to be more problematic for non-native English speakers. In real life, however, mTDS users do not have a mandate to only use the speech recognition mode for typing. Occasionally, they can take advantage of the TDS modality for typing in order to achieve a higher level of accuracy, for instance when the speech recognition software does not recognize their spoken input because of their accent or

Table 9.2: Effect of Different Factors on mTDS Maze Navigation Performance

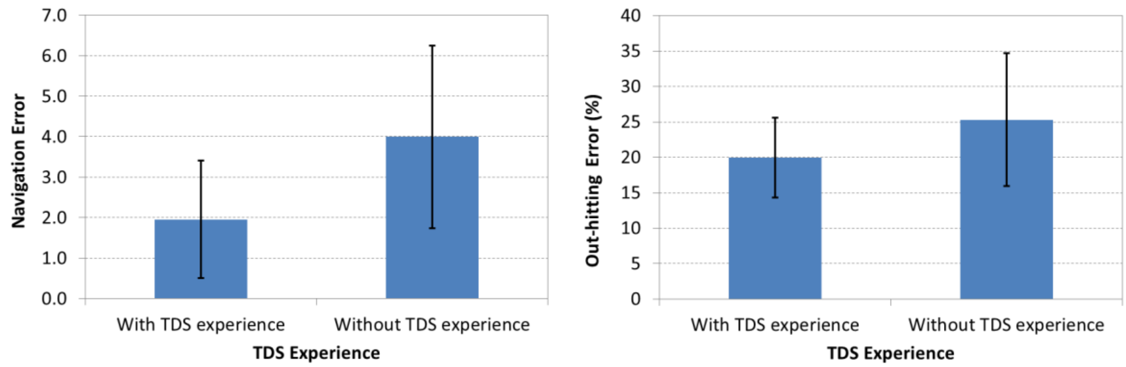
Performance measures		Total Time	Navigation Time	Typing Time	Navigation Error	Typing Error
With TDS exp.		82.7±9.0	33.4±5.4	49.4±7.7	2.0±2.0	4.7%±4.2%
Without TDS exp.		101.2±23.2	44.6±18.5	56.5±14.2	4.0±2.8	3.4%±3.0%
Native Speaker		97.6±14.4	42.6±16.4	55.0±11.5	4.3±3.0	2.6%±2.9%
Non-native Speaker		86.3±23.1	35.4±12.2	50.9±12.3	1.6±1.1	5.5%±3.8%
TDS Exp.	*Sig*	0.017*	0.046*	0.171	0.248	0.984
	Power	0.678	0.521	0.275	0.208	0.050
Eng. Accent	*Sig.*	0.534	0.542	0.799	0.022*	0.222
	Power	0.094	0.092	0.057	0.645	0.218
*TDS Exp. * Eng. Accent*	*Sig.*	0.308	0.458	0.494	0.387	0.587
	Power	0.172	0.113	0.103	0.137	0.080

Table 9.3: Effect of Different Factors on mTDS Center-out Tapping Performance

Performance measures		Total Time	Navigation Time	Typing Time	Through -put	Error Rate	Typing Error
With TDS exp.		95.8±14.4	47.3±8.6	48.5±7.1	1.4±0.3	19.9±7.6	7.7%±5.7%
Without TDS exp.		112.2±19.5	59.9±13.2	52.3±11.8	1.1±0.3	25.3±12.6	5.1%±3.5%
Native Speaker		104.2±20.2	57.7±13.9	46.5±8.9	1.0±0.3	23.8±13.5	4.7%±4.2%
Non-native Speaker		103.8±18.4	49.5±10.4	54.3±9.1	1.4±0.3	21.4±6.9	8.1%±5.0%
TDS Exp.	*Sig*	0.003*	0.007*	0.016*	0.04*	0.483	0.637
	Power	0.863	0.797	0.691	0.567	0.101	0.073
Eng. Accent	*Sig.*	0.207	0.374	0.002*	0.966	0.792	0.356
	Power	0.240	0.142	0.903	0.050	0.057	0.142
*TDS Exp. * Eng. Accent*	*Sig.*	0.735	0.497	0.174	0.191	0.628	0.632
	Power	0.063	0.103	0.271	0.245	0.074	0.073

when the environmental noise is high.

To examine the effect of different factors on the mTDS performance, we have categorized the subjects based on their prior TDS experience (7 experienced and 7 naïve subjects) and English accent (7 native and 7 non-native English speakers). We have applied Two-way ANOVA on all the performance measures considering both factors. The results are summarized in Table 9.2 and Table 9.3.



(a) (b)

Figure 9.12: The effect of prior TDS experience on cursor navigation accuracy: a) Average navigation error in maze navigation experiment, and b) Out-hitting error in center-out tapping experiment.

The effect of prior TDS experience is significant on the total completion time and the navigation time in both maze and center-out experiments. In addition, the *TP* of TDS experienced subjects was significantly higher than that of naïve TDS users in center-out tapping experiment. These results showed that the subjects with prior TDS experience have better control over mouse cursor when using mTDS, and can complete the tasks more efficiently compared with TDS novice. No enough evidence was found to state that the effect of prior TDS experience was significant on the navigation error in maze navigation and out-hitting error in center-out tapping. Post-hoc power analysis showed that there was actually not enough power to detect that effect for these two performance measures due to the small number of subjects in each group. However, we found consideration difference between two groups of subjects by directly comparing the average value of these two measures as shown in Figure 9.12. The large variations compared with the amplitude of the mean values, reduced the effect size and resulted in low power in data analysis. The variations are expected to become smaller when the number of subjects increases, which will make the effect of TDS experience more

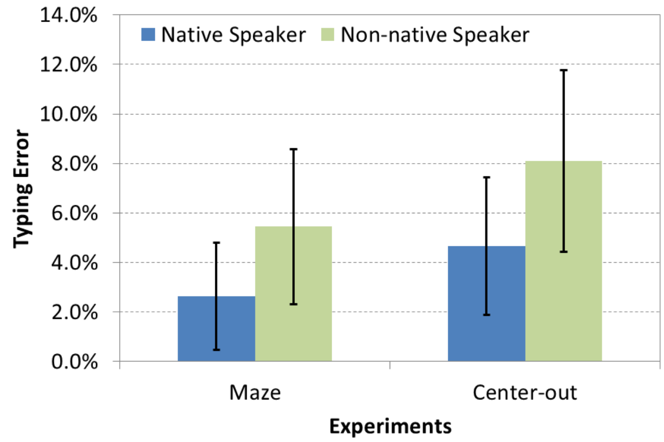


Figure 9.13: The effect of English accent on the typing error in both maze navigation and center-out tapping experiments.

pronounced. Statistically analysis showed that the TDS experienced users typed significantly faster than TDS novices in the center-out experiment. This result was not expected since the typing was completed using speech modality in this case. In fact, two of our TDS experienced subjects also had prior experience with Dragon and were able to type faster than other subjects. This could bias the results considering the limited number of subjects in each category.

Regarding the effect of English accent, the native English-speaking subjects completed the typing tasks significantly faster than non-native English speaking subjects in center-out tapping experiment. Statistically, there was no enough evidence to claim significant effect of English accent on the typing accuracy, probably due to same reason mentioned above, e.g. the limited number of subjects resulting low power in the analysis. However, as shown in Figure 9.13, despite the large variations, the magnitudes of typing error associated with the native speakers were consistently lower than that with non-native speakers in both maze and center-out experiments. Recruiting more subjects will reduce the variations and therefore give us more power to detect the significance of

English accent. We also observe unexpected significant effect of English accent on the navigation error in maze navigation experiment. Basically, non-native speakers can navigate significantly faster than native speakers. This was probably related to the factor that most of our TDS experienced subjects (5 out of 7) were non-native speakers.

9.6 Summary

We have evaluated and compared the performance of mTDS with its unimodal counterparts, e.g. TDS alone and speech recognition alone, in completing comprehensive computer access tasks, where both text entry and cursor navigation are necessary. Preliminary results from fourteen able-bodied subjects showed that the mTDS can significantly improve the speed of completing these tasks. It was also demonstrated that using the mTDS does not affect the user's performance with either one of the two modalities. All subjects reported that they prefer to use mTDS over TDS or speech recognition alone for computer access if they were not able to use mouse and keyboard. The subjects with prior TDS experience could perform the tasks more efficiently than TDS novices. We also observed the significant effect of English accent on typing time in center-out experiment. No significant effect of accent has been discovered on the typing error due to the low power in ANOVA as a result of limited number of subjects in each group. However, the mean values of typing error associated with native English speakers were much lower than non-native English speaker in both experiments. We expect the effect to be more pronounced if we had more subjects.

CHAPTER X

CONCLUSIONS

10.1 Contributions

The presented research seeks to develop, characterize, and assess the usability of a novel wireless tongue-operated assistive technology called the Tongue Drive System (TDS), which allows individuals with severe disabilities (such as quadriplegics) to access computers, drive powered wheelchairs and control their environments, using their voluntary tongue motion with minimum additional physical or psychosocial burden.

The most significant contributions of this research are first, development of a portable and wearable wireless platform to verify and validate the proposed TDS technology, e.g. detecting and extracting users' intention from their voluntary tongue motion through utilizing a combination of magnetic tracer attached to the tongue and an array of magnetic sensors. The modular design of the platform allows it to be easily integrated or combined with exiting assistive technologies, such as standard powered wheelchairs, augmentative and alternative communication (AAC) devices, and electronic aids to daily living (EADLs), with minimum modifications.

Second, the performance of the developed platform, including a group of low power electronics, a customized set of computational effective sensor signal processing algorithms and a set of user-friendly graphical user interfaces, has been evaluated by both able-bodied subjects and the patients with high level spinal cord injuries in single-session human trials. The results have demonstrated that the TDS technology in its current form has the potential to partially substitute the lost hand and arm functions and provide its end users with effective control over both computers and PWCs.

The third achievement is the quantitative and comparative assessment of the learning process of using the TDS technology for both computer access and wheelchair control. The results provided valuable insights about tongue human factors, which can lead the way in improving the usability of the TDS and similar tongue operated assistive technologies. It also helped to refine the instructions and user manuals of the TDS that serves as an important tool to help not only the end users but also their caregivers learn to setup and operate the TDS.

Last but not the least, a multimodal TDS (mTDS) prototype, which utilizes both tongue motion and speech as input modalities, was developed and evaluated by able-bodied subjects. It was demonstrated that the system could take advantage of the strength of each modality to provide its users with more efficacious, flexible, and reliable computer access. To the best of author's knowledge, mTDS is the first highly integrated multimodal and multifunctional technology that has been realized in the form of a unified, compact, unobtrusive, lightweight, completely wireless, and wearable device, which can be used in different environments for a variety of purposes, range of abilities, and personal preferences.

10.2 Future Work

The work performed to date has created a solid theoretical and technical basis for the development of the TDS in the context of assistive technology. However, a considerable amount of work remain to be done before TDS can be accepted, used and appreciated by its end users as a technology that could help them on daily basis.

First, the size, weight, and the power consumption of the current TDS hardware should be further reduced to facilitate the design and fabrication of a new light-weighted custom-designed headset, while the other specifications of the hardware, i.e. the sensor sensitivity, sampling rate and signal-to-noise ratio, should be maintained and even improved. In addition, a Bluetooth module, such as Bluetooth low energy, can be used to replace the proprietary low power RF wireless transceiver in the current headset to improve the ubiquitous accessibility of the TDS. As a result, TDS can be accessed from any smart phone, laptop or desktop which is equipped with Bluetooth without an add-on wireless receiver.

Second, the performance and end user coverage of current TDS can be further enhanced by adding other input modalities, such as head control using commercial motion sensors. In the current mTDS, the commands from different modalities, e.g. tongue and voice commands are used to operate their dedicated devices or complete dedicated tasks individually. In addition, these commands can be fused together to enrich the control of one device at a time and achieve a higher control accuracy and bandwidth in demanding tasks such as being able to activate numerous controls on a gaming console as well as various shortcuts.

Third, the TDS can also be used as an input device for electronic aids to daily life (EADLs) or environmental control units (EDUs) to interact and manipulate electronic appliance such as: a television, radio, CD player, lights, and fan etc., in a smart home environment. The commercially available EDAL devices receive their control commands from a central controller, i.e. a computer, a touch screen terminal or simply an array of switches, and then communicate with the remote devices through RF, infrared, ultrasonic or power lines using the widely accepted X10 protocol. In the TDS, a PC or a smartphone that runs the SSP algorithm can communicate with the EADL devices through USB or wireless link after converting TDS commands into a format that can be recognized by these commercial devices. In this way, a new set of functions for environmental control can be added to the TDS with minor modifications.

During the human trials, several subjects reported reduced or even complete loss of sensitivity to some of their tongue commands due to a shift in the position of the headset, in which case the training steps had to be repeated. This problem can be resolved by developing an intraoral version of TDS (iTDS), which requires to radically shrink the size of all TDS electronic components to the level that they can be hermetically sealed and embedded in a dental retainer, to be worn comfortably inside the mouth. The iTDS dental retainers can be customized to the users' oral anatomy by orthodontists to firmly clasp to their teeth and reduce the range of displacements. The iTDS can significantly improve the reliability, performance, safety, and acceptability of this assistive technology by resolving the mechanical stability problem while being completely inconspicuous, hidden inside the mouth.

As far as the SSP algorithm is concerned, the current algorithm will be optimized to improve the command classification accuracy and to solve the "junk commands" problem. These are random unintended commands that are sometimes issued as the user moves his/her tongue from one command to another. New SSP algorithms, such as those based on support vector machines (SVMs), should be explored and evaluated to increase the number of tongue commands, possibly, from six (coarse mode) to twelve (fine mode). Proportional control capability should definitely be explored and added to the current TDS to provide its end users with much easier, smoother, and more natural control over computer mouse cursor or powered wheelchairs. In addition, the training and calibration processes should be significantly simplified, improved and automated so that they can be initiated and completed by users in a much shorter time (less than 1 minute) without the intervention from a caregiver.

One big advantage of TDS is that a single, compact, highly integrated system can be used to control multiple devices in users' environment without the need of switching among different ATs. In order to achieve this goal, customized graphical user interfaces (GUIs) should be designed to allow users to easily, smoothly, and quickly switch TDS from controlling one device to another without receiving any assistance from their caregivers or family members. For instance, the TDS users should be able to drive their wheelchairs around using TDS via an iPhone, and quickly switch to computer control mode with simple interactions with the GUIs running on the iPhone when they want to use the computer. They should also be able to quickly switch back to wheelchair control mode with minimal effort to do a weight shift in the middle of using computer.

Finally, the TDS so far has only been evaluated in well-controlled research environments, such as in a research lab or a rehabilitation center with the presence of either research personal or occupational practitioners for limited period of time. In the future, such performance evaluation should also be conducted by its end users, e.g. quadriplegics, in their home, office and even outdoor environments with the presence of only their caregivers or family members who have limited knowledge about technology and engineering, on a daily basis. This will reveal the issues related to installing, operating, and maintaining the TDS in the most realistic configuration and ultimately help improving TDS's usability and user acceptability.

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